Technical Report CERC-96-7
September 1996

US Army Corps of Engineers
Waterways Experiment Station

Study of Harbor Improvements at St. Paul Harbor, St. Paul Island, Alaska

Coastal Model Investigation

by Robert R. Bottin, Jr.

Prepared for U.S. Army Engineer District, Alaska

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Final report

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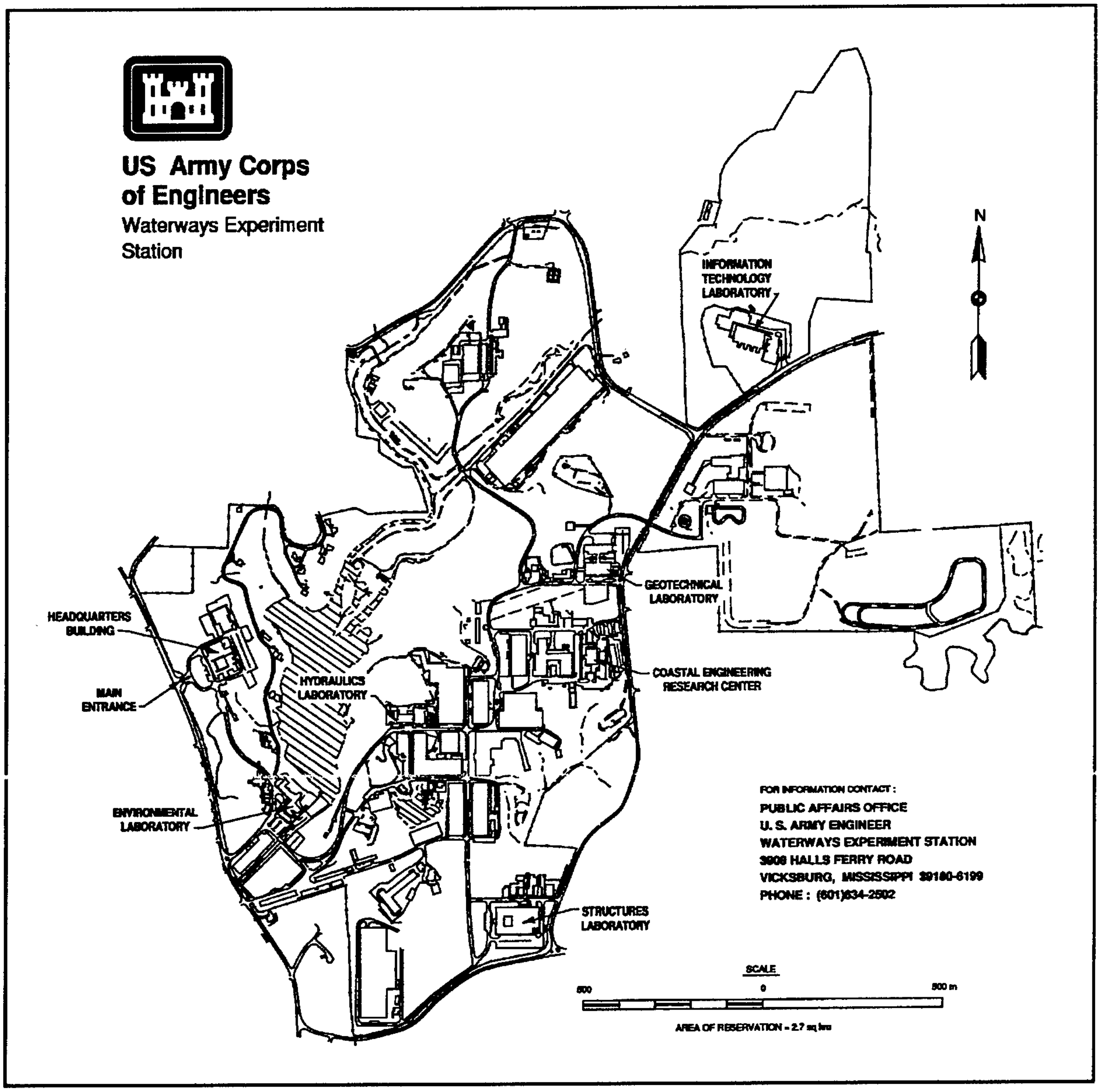
Anchorage, Alaska 99506-0898



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Contents

Preface

A request for a model investigation to study harbor modifications at St. Paul Harbor, St. Paul Island, Alaska, was initiated by the U.S. Army Engineer District, Alaska, (NPA), in a letter to the U.S. Army Engineer Division, North Pacific (NPD). Authorization for the U.S. Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), to perform the study was subsequently granted by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Funds were provided by the NPA on 11 and 23 October, and 22 November 1995, and 4 and 23 January 1996.

Model tests were conducted at WES during the period December 1995 through February 1996 by personnel of the Wave Processes Branch (WPB), Wave Dynamics Division (WDD), CERC, under the direction of Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., Director and Assistant Director, CERC, respectively; and under direct guidance of Messrs. C. E. Chatham, Jr., Chief, WDD; and Dennis G. Markle, Chief, WPB. Model tests were conducted by Messrs. Larry R. Tolliver and Hugh F. Acuff, Civil Engineering Technicians, and William G. Henderson, Computer Assistant, under the supervision of Mr. Robert R. Bottin, Jr., Research Physical Scientist. Mr. Henderson performed all data analysis during the investigation. This report was prepared by Mr. Bottin.

Prior to the model investigation, Messrs. Bottin and Tolliver met with representatives of NPA and visited the St. Paul Harbor site. During the course of the study, liaison was maintained by means of conferences, telephone communications, and monthly progress reports. Mr. Ken Eisses was technical point of contact for NPA. The following personnel visited WES to attend conferences and/or observe model operation during the course of the study.

Mr. John H. Lockhart	HQUSACE
Mr. Ed Price	HQUSACE
Mr. Dave Reece	HQUSACE
Mr. James Daniek	HQUSACE
Ms. Arlene Dietz	HQUSACE
Mr. Brad Bird	NPD
Mr. Thomas L. Davis	NPD
Mr. Morley M. Hofer	NPD

Mr. Dennis Wagner	NPD
Mr. Tom White	NPD
Mr. J. R. Reese	NPD
Mr. Ken Hitch	NPA
Mr. Claude Vining	NPA
Mr. Ken Eisses	NPA
Mr. Alan Jeffries	NPA
Mr. John Burns	NPA
Mr. Andrew Miller	NPA
Mr. Clarke Hemphill	NPA
Mr. John Oliver	Consultant, NPA
Mr. Harvey Smith	Alaska Department of Transportation
Ms. Laurie Fairchild	U.S. Fish and Wildlife Service
Mr. Brad Smith	National Marine Fisheries
Mr. George Watts	Consultant, City of St. Paul
Mr. Mark Fregberg	Natural Resources Consultants
Mr. Jeff June	Natural Resources Consultants
Mr. Michael Dahl	Polar Consultants
Mr. Andrey Mandregan, Jr.	City of St. Paul
Mr. John R. Merculief	City of St. Paul
Mr. Carl W. Merculief	City of St. Paul
Mr. Simeon Swetzof, Jr.	City of St. Paul
Mr. Myron Melovidov	City of St. Paul
Mr. Tony Smith	City of St. Paul
Mr. Michael Lamb	City of St. Paul
Ms. Charlotte Kirkwood	City of St. Paul
Mr. Robert Britch	Northern Consulting/Tanadgusix (TDX) Corporation
Mr. Elary Gromuff, Jr.	TDX Corporation

Dr. Robert W. Whalin was Director of WES during model testing and the preparation and publication of this report. COL Bruce K. Howard, EN, was Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4046.873	square meters
cubic feet per second	0.02831685	cubic meters per second
cubic yards	0.7646	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
feet per second	0.3048	meters per second
inches	2.54	centimeters
knots (international)	1.8532	kilometers per hour
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4536	kilograms
pounds (mass) per cubic feet	16.02	kilograms per cubic meter
square feet	0.09290304	square meters
square miles (U.S. statute)	2.589988	square kilometers
tons (2,000 lb, mass)	907.1848	kilograms

1 Introduction

Prototype

St. Paul Island is the northernmost and largest island of the Pribilofs in the eastern Bering Sea (Figure 1) with a land area of 114 sq km (44 sq mi).[1] The Pribilofs are of volcanic origin, and St. Paul Island is composed predominantly of volcanic materials in the form of lava flows and loose cinders with sandy deposits. The west and southwest portions of the island are relatively high and mountainous with precipitous cliffs along the coast. The remainder of the island is relatively low and rolling with a number of extinct volcanic peaks scattered throughout. Only two of the Pribilof Islands are populated, St. Paul with 800 people and St. George with 290 people. Two-thirds of the St. Paul population is Alaskan Native.

The Pribilof Islands support large populations of birds, mammals, fish, and invertebrates. The Pribilofs are the primary breeding ground for northern fur seals where approximately two-thirds of the world's population (1.3 to 1.4 million) migrate annually (U.S. Army Engineer District (USAED), Alaska (USAED, Alaska 1981). More than a quarter million seabirds nest on St. Paul Island each year, mainly along the coastal cliffs. The uplands are inhabited by song birds, white and blue foxes, and a transplanted herd of approximately 250 reindeer. The island is treeless and covered with grasses, sedges, and wildflowers. The eastern Bering Sea near St. Paul supports populations of shrimp, commerically harvestable species of crab, and bottom fish.

The city of St. Paul is located on a cove on the southern tip of the island and is the island's only settlement. The islands were originally settled by the Russians to harvest fur seals. The treaty for the purchase of Alaska from Russia by the U.S. in 1867 placed the Priblofs under United States control. The National Marine Fisheries Service (NMFS) and its predecessor Federal agencies were responsible for the fur seal industry in the Pribilofs since 1911, managing the harvest according to a series of

[1] Units of measurement in this report are shown in SI units, followed by non-SI (British) units in parentheses. In addition, a table of factors for converting non-SI units of measurement used in plates, figures, photos, and tables in this report to SI units is presented on page vi.

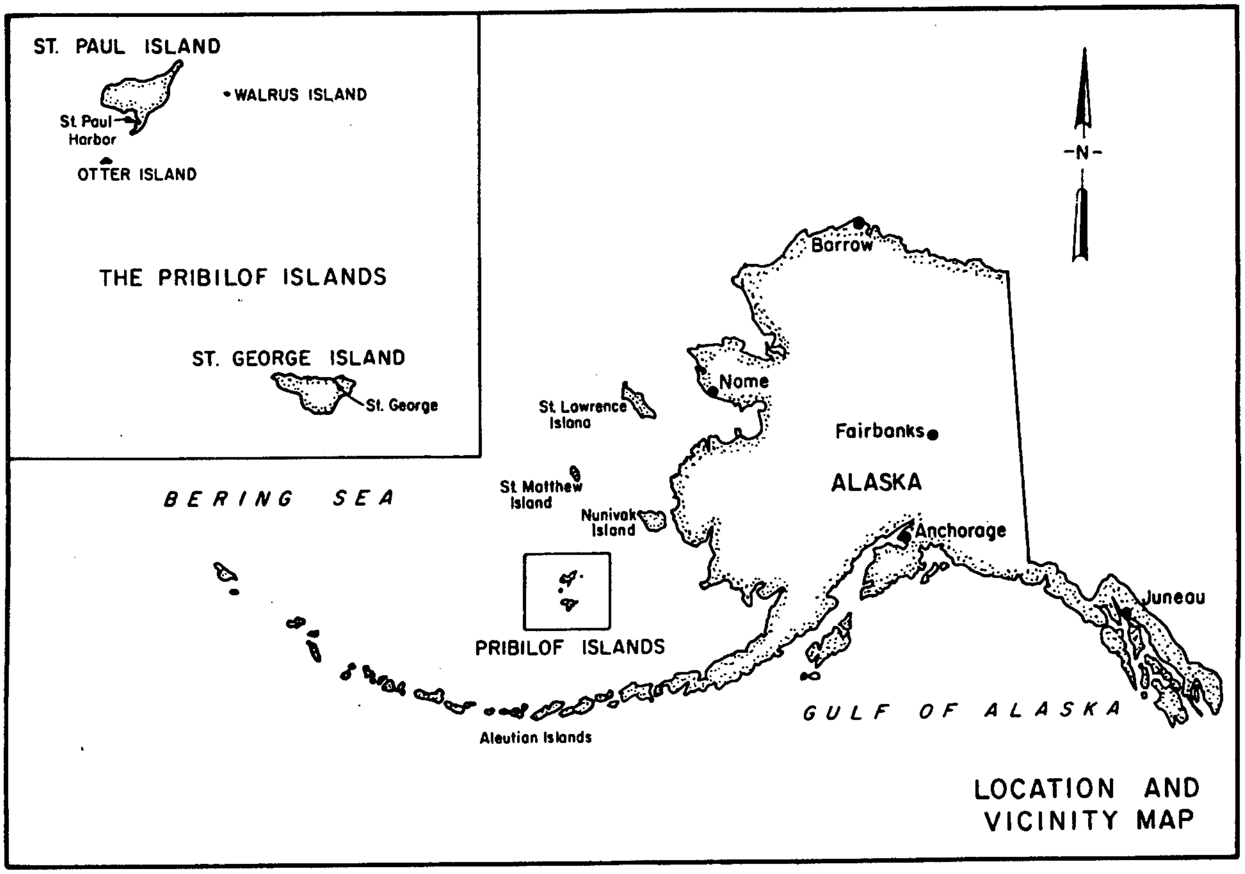

Figure 1. Project location

international agreements between the United States, Canada, Japan, and the Soviet Union. In 1983, the harvest of fur seals was discontinued due to a seal harvest moratorium. The NMFS terminated administration, management, and employment at St. Paul. This event had a significant adverse impact on the economy, and the standard of living could not be maintained. At that time the village had no other economic base, no harbor infrastructure, inadequate and unpermitted utilities, overcrowded housing, high unemployment, and limited air and vessel transportation. Development of a harbor and associated marine related industries fulfilled the need for new sources of employment and income on the island.

Harbor Development

A breakwater was constructed at St. Paul in Village Cove during 1984, but subsequently failed during storms of 1984. A new breakwater was designed and constructed by Tetra Tech, Inc. in 1985, consultants to the City of St. Paul (Tetra Tech, Inc. 1987). The structure was 229 m (750 ft) in length and functioned well, in regard to stability, during the 1985 and 1986 winter seasons. A 61-m-long (200-ft) vertical-wall dock was installed in the lee of the breakwater in 1986 to accomodate fishing

vessels. The breakwater, however, was not of sufficient length to provide wave protection to vessels using the dock, particularly during storm events.

In 1989, construction of the current harbor was completed. It consists of a 549-m-long (1,800-ft) main breakwater, a 296-m-long (970-ft) detached breakwater, and 274-m (900-ft) dock space on the lee side of the main breakwater. The main breakwater, generally, follows the -7.6-m (-25-ft)[1] contour in Village Cove and results in a harbor with 32,375 to 40,470 sq m (8 to 10 acres) of area and water depths of 5.5 to 7.6 m (18 to 25 ft) on the lee side of the breakwater. The center line of the detached breakwater makes an interior angle of 75 deg with the main structure at sta 17+00, and provides a 91-m-wide (300-ft-wide) harbor entrance. A 61-m-wide (200-ft-wide) opening between the eastern end of the detached breakwater and the shore is maintained to enhance harbor circulation. An aerial photograph of the existing St. Paul Harbor is shown in Figure 2.

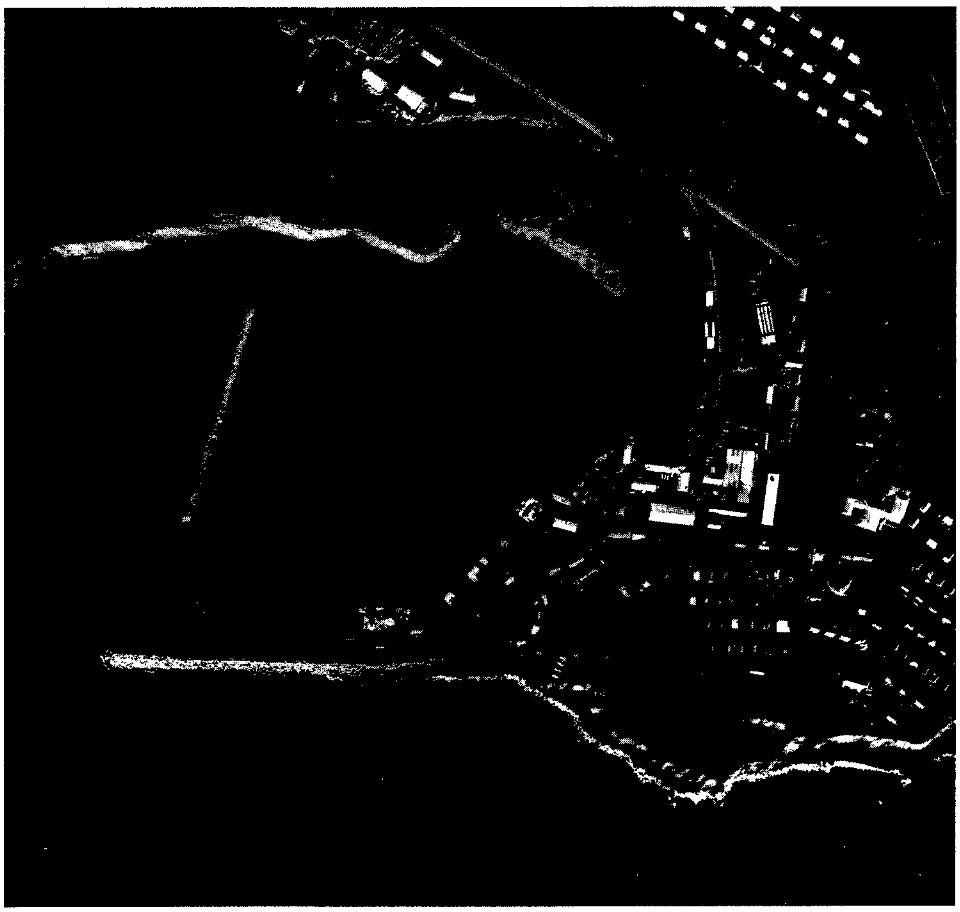

Figure 2. Aerial view of St. Paul Harbor

[1] All contours and elevations cited herein are in meters (feet) referred to mean lower low water (mllw), unless otherwise noted.

breakwater and the shore is maintained to enhance harbor circulation. An aerial photograph of the existing St. Paul Harbor is shown in Figure 2.

The main breakwater has a crest elevation (el) of +11.3 m (+37 ft) from sta 7+50 to a point approximately 15.2 m (50 ft) north of the northernmost dock. The remaining portion of the structure has a crest el of +9.1 m (+30 ft). Armor stone used on the breakwater trunk was 16,330 kg (18 ton), and 21,770 kg (24 ton) armor stone was used on the head. The slope of the trunk is 1V:2H with a 1V:3H slope around the breakwater head. A roadway was constructed on the lee side of the main breakwater adjacent to the proposed docks. The detached breakwater has a crest el of +5.5 m (+18 ft) with 4,535-kg-(5-ton) armor stone placed on a slope of 1V:1.5H. Prior to construction of the 1989 improvements, both two-dimensional (2-D) (Ward 1988) and three-dimensional (3-D) (Bottin and Mize 1988) hydraulic model investigations were conducted at the U.S. Army Engineer Waterways Experiment Station (WES) to optimize structural and functional design of the harbor.

Problems and Needs

When constructed in 1989, St. Paul Harbor was designed to support a fishing fleet one-third the size of the current operating fleet. It was not intended that the harbor have floating or shore-based processing plants. It was designed only to accomodate unladen fishing vessels going into the harbor to refuel and stock provisions. Large loaded vessels were not expected to use the harbor because processing facilities were located outside the harbor. The design vessel was 33.5 m (110 ft) in length and drafted 3.7 m (12 ft) unladen.

St. Paul Harbor currently serves a fleet of 230 transient vessels during the crabbing season. In 1994, a total of 27 floating processors were located within a 4.8-km (3-mile) limit of the harbor. St. Paul is in a rapid growth cycle. Established seafood processors are investing capital to relocate and build processing plants there. Unisea moved a floating crab processing plant from Dutch Harbor to the lee side of the main breakwater, and Icicle Seafoods has moored a processor to the local Native corporation (Tanadgusit (TDX)) dock. In the harbor, Unipak has established an onshore plant. The Unipak plant is capable of processing halibut, cod, and pollock, in addition to crab, opening the possibility of expanded fisheries processing in the area (USAED, Alaska 1995).

When more than one vessel in the harbor needs fuel, delay can be for several hours at the fuel dock. During the crabbing season, the fuel dock is closed a minimum of 3 hr at least once each week when cargo vessels deliver supplies to the harbor. In addition, the harbor must be closed at random intervals due to weather. Due to the lack of a turning basin, smaller fishing vessels are forced to move to accommodate larger vessels when the harbor is crowded or when large ships are in port. Limited space

Large vessels and processors operating in the eastern Bering Sea travel to Dutch Harbor to deliver their catches due to the lack of room and shallow draft in St. Paul Harbor. Dutch Harbor is farther from the fishing grounds than St. Paul. Some vessel operators have indicated that if the harbor were deeper and had a turning basin, they would unload their catches at St. Paul to save fuel and travel time. Vessels in distress also have been towed to Dutch Harbor from the fishing grounds, because there is no place for them to tie up at St. Paul without impacting the already congested harbor. Fishermen injured, due to accidents, are taken to the St. Paul Clinic for treatment. Vessels in the harbor are sometimes forced to move to allow the entrance of a vessel in distress or a vessel dropping off injured fishermen.

Purpose of Model Study

The U.S. Army Engineer District, Alaska (NPA), is studying the feasibility of deepening the entrance channel and dredging a deeper and larger maneuvering basin at St. Paul Harbor to relieve the current congestion. At the request of NPA, a physical coastal hydraulic model investigation was initiated by WES to:

a. Determine impacts of the proposed harbor improvements on wave conditions, wave-induced current patterns and magnitudes, and sediment patterns and subsequent deposits in the harbor and entrance channel.

b. Determine impacts of proposed submerged reef concepts on wave-induced current patterns and magnitudes and sediment tracer patterns and subsequent deposits seaward of the main breakwater and entrance channel.

c. Develop remedial plans for the alleviation of undesirable conditions as found necessary.

A 2-D model investigation was conducted at WES concurrently with this 3-D model study to develop plans for alleviation of overtopping of the main breakwater. Results of the 2-D study are reported separately (Ward in preparation).

2 The Model

Design of Model

The St. Paul Harbor model (Figure 3) was constructed to an undistorted linear scale of 1:100, model to prototype. Scale selection was based on the following factors:

a. Depth of water required in the model to prevent excessive bottom friction.

b. Absolute size of model waves.

c. Available shelter dimensions and area required for model construction.

d. Efficiency of model operation.

e. Available wave-generating and wave-measuring equipment.

f. Model construction costs.

A geometrically undistorted model was necessary to ensure accurate reproduction of wave and current patterns. Following selection of the linear scale, the model was designed and operated in accordance with Froude's model law (Stevens et al. 1942). The scale relations used for design and operation of the model were as follows:

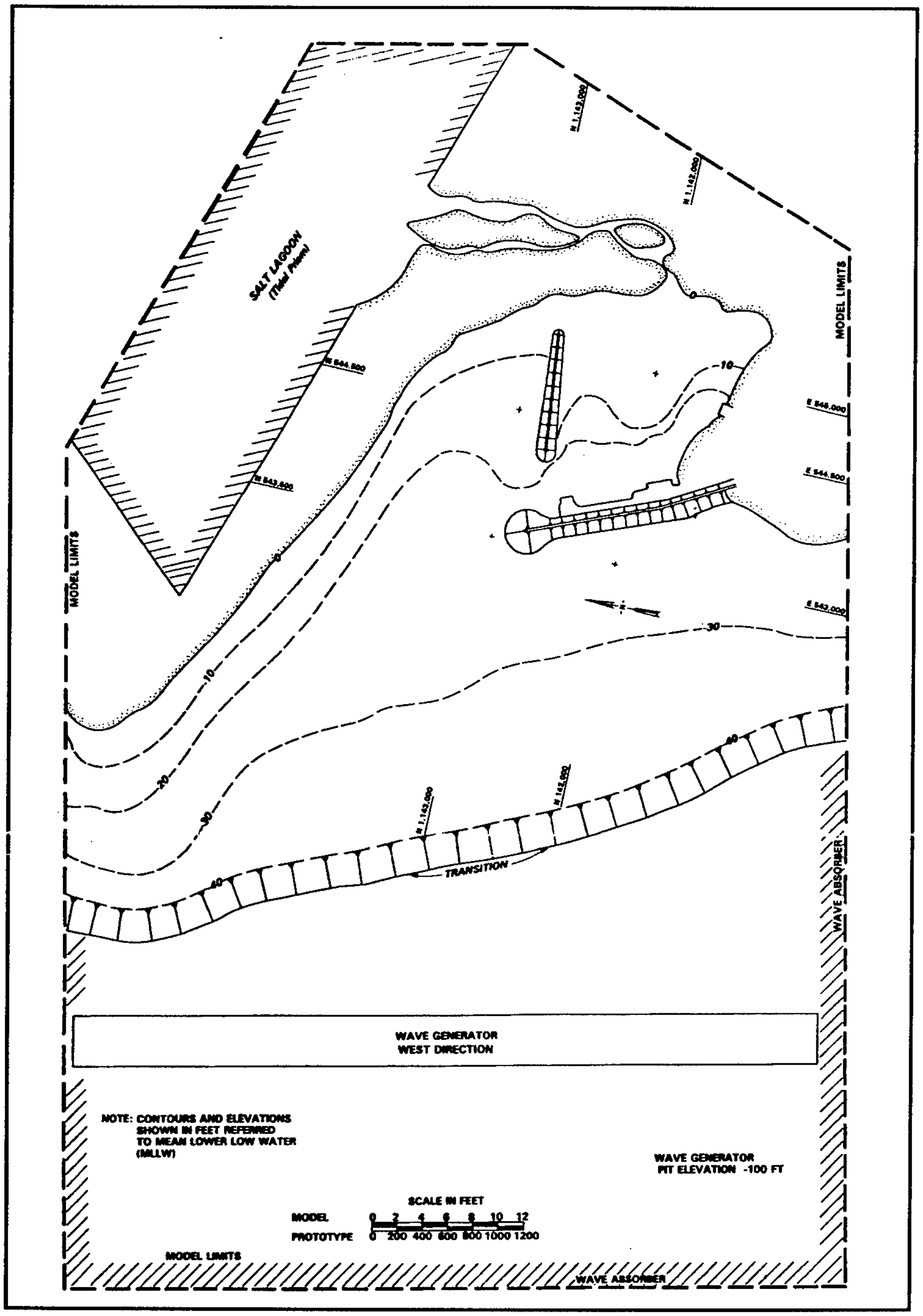

Figure 3. Model layout

Characteristic	Model-Prototype Dimension[1]	Scale Relations
Length	L	$L_r = 1:100$
Area	L^2	$A_r = L_r^2 = 1:10,000$
Volume	L^3	$V_r = L_r^3 = 1:1,000,000$
Time	T	$T_r = L_r^{1/2} = 1:10$
Velocity	L/T	$V_r = L_r^{1/2} = 1:10$

[1] Dimensions are in terms of length (L) and time (T).

The existing breakwaters and proposed reefs at St. Paul Harbor are rubble-mound structures. Experience and experimental research have shown that considerable wave energy passes through the interstices of this type structure; thus, the transmission and absorption of wave energy became a matter of concern in the design of 1:100-scale model. In small-scale hydraulic models, rubble-mound structures reflect relatively more and absorb or dissipate relatively less wave energy than geometrically similar prototype structures (LeMehaute 1965). Also, the transmission of wave energy through a rubble-mound structure is relatively less for the small-scale model than for the prototype. Consequently, some adjustment in small-scale model rubble-mound structures is needed to ensure satisfactory reproduction of wave-reflection and wave-transmission characteristics. In past investigations (Dai and Jackson 1966, Brasfeild and Ball 1967) at WES, this adjustment was made by determining wave-energy transmission characteristics of the proposed structure in a 2-D model using a scale large enough to ensure negligible scale effects. A cross section then was developed for the small-scale, 3-D model that would provide essentially the same relative transmission and reflection of wave energy. Therefore, from previous findings for structures and wave conditions similar to those at St. Paul Harbor, it was determined that a close approximation of the correct wave-energy transmission and reflection characteristics could be obtained by increasing the size of the rock used in the 1:100-scale model to approximately two times that required for geometric similarity. Accordingly, in constructing the rubble-mound structures in the St. Paul Harbor model, rock sizes were computed linearly by scale, then multiplied by 2 to determine the actual sizes to be used in the model.

Ideally, a quantitative, 3-D, movable-bed model investigation would best determine the impacts of harbor modifications with regard to sediment deposition in the vicinity of the harbor. However, this type model investigation is difficult and expensive to conduct, and each area in which such an investigation is contemplated must be carefully analyzed. In view of the complexities involved in conducting movable-bed model studies and because of limited funds and time for the St. Paul Harbor project, the model was molded in cement mortar (fixed-bed), and a tracer material was obtained to qualitatively determine sediment patterns in the vicinity of the harbor.

Model and Appurtenances

The model reproduced approximately 2,865 m (9,400 ft) of the St. Paul Island shoreline (from Tolsti Point easterly and then southerly to a point south of the existing breakwater trunk), the existing harbor, and underwater topography in the Bering Sea to an offshore depth of 12.2 m (40 ft) with a sloping transition to the wave generation pit elevation of -30.5 m (-100 ft). A small connecting channel to a salt lagoon (located east of the harbor) also was included in the model as well as the tidal prism of the salt lagoon. The total area reproduced in the model was approximately 605 sq m (6,500 sq ft), representing about 6 sq km (2.3 sq mi) in the prototype. Vertical control for model construction was based on mean lower low water (mllw), and horizontal control was referenced to a local prototype grid system. A general view of the model is shown in Figure 4.

Model waves were reproduced by an 18.3-m-long (60-ft-long), electrohydraulic, unidirectional, spectral wave generator with a trapezoidal-shaped plunger. The vertical motion of the plunger was controlled by a computer-generated command signal, and movement of the plunger caused a displacement of water which generated required test waves.

An Automated Data Acquisition and Control System, designed and constructed at WES (Figure 5), was used to generate and transmit wave generator control signals, monitor wave generator feedback, and secure and analyze wave data at selected locations in the model. Through the use of a microvax computer, the electrical output of parallel-wire, capacitance-type wave gauges, which varied with the change in water-surface elevation with respect to time, was recorded on magnetic disks. These data then were analyzed to obtain the parametric wave data.

A 0.6-m (2-ft) (horizontal) solid layer of fiber wave absorber was placed along the inside perimeter of the model to dampen wave energy that might otherwise be reflected from the model walls. In addition, guide vanes were placed along the wave generator sides in the flat pit area to ensure proper formation of the wave train incident to the model contours.

Design of Tracer Material

As discussed previously, a fixed-bed model was constructed and a tracer material selected to qualitatively determine movement and deposition of sediment in the vicinity of the harbor. Tracer material was chosen in accordance with the scaling relations of Noda (1972), which indicates a relation, or model law, among the four basic scale ratios, i.e., the horizontal scale, λ; the vertical scale, μ; the sediment size ratio, η_D; and the relative specific weight ratio, η_γ. These relations were determined experimentally using a wide range of wave conditions and bottom materials and are valid mainly for the breaker zone.

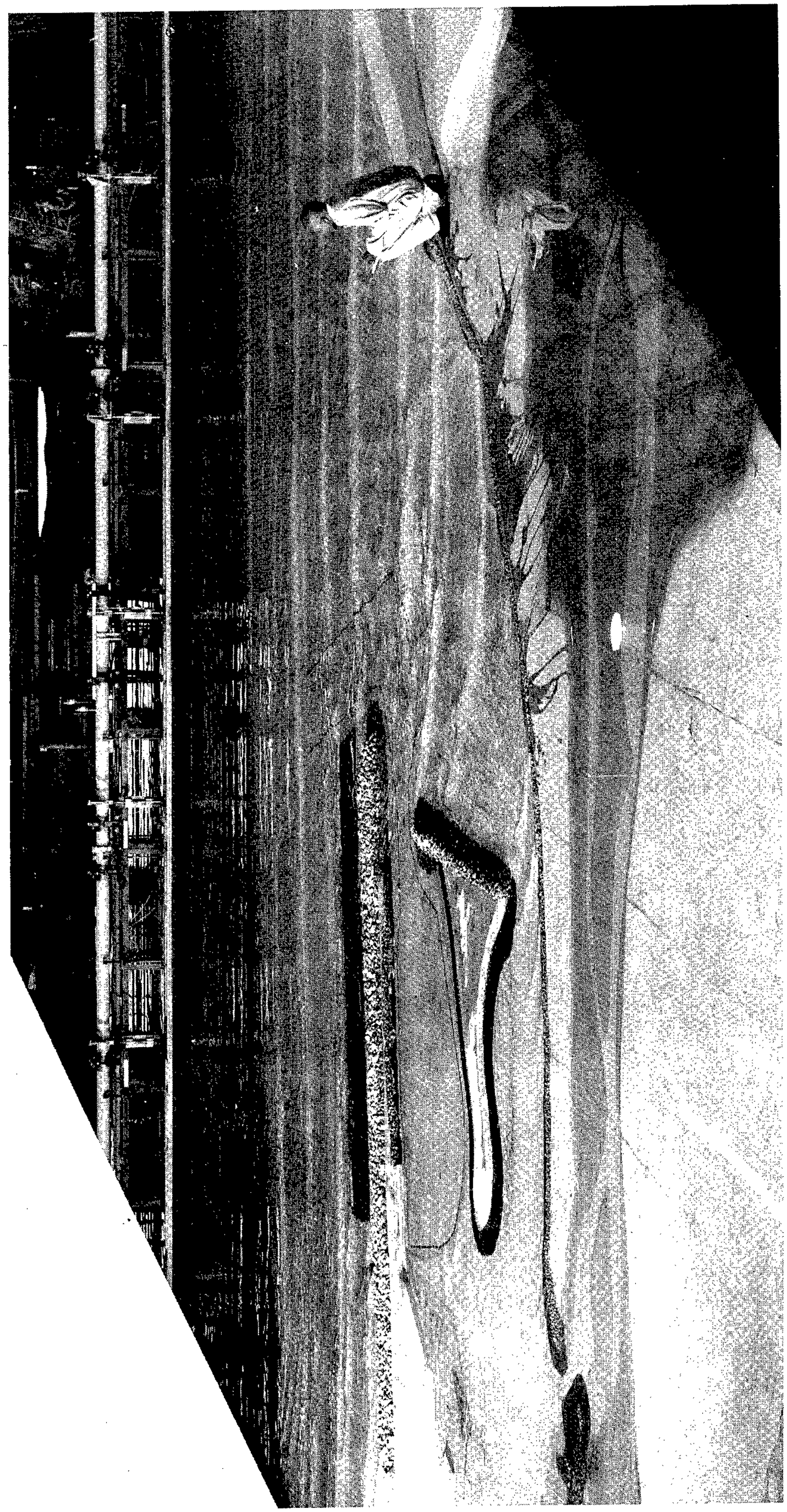

Figure 4. General view of model

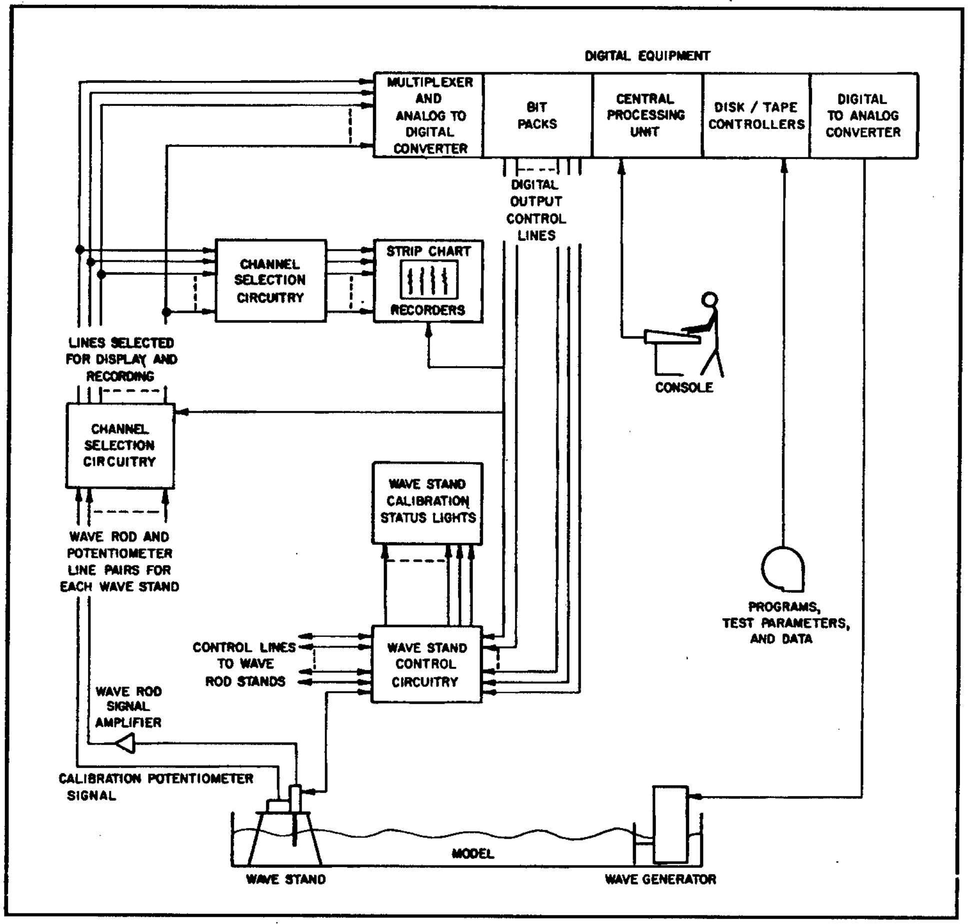

Figure 5. Automated data acquisition and control system

Noda's scaling relations indicate that movable-bed models with scales in the vicinity of 1:100 (model to prototype) should be distorted (i.e., they should have different horizontal and vertical scales). Since the fixed-bed model of St. Paul Harbor was undistorted to allow accurate reproduction of short-period wave and current patterns, the following procedure (which has been successfully used and validated for undistorted models) was used to select a tracer material. Using the prototype sand characteristics (median diameter, D_{50} = 0.19 mm, specific gravity = 2.82) and assuming the horizontal scale to be in similitude (i.e., 1:100), the median diameter for a given vertical scale was then assumed to be in similitude and the tracer median diameter and horizontal scale were computed. This resulted in a range of tracer sizes for given specific gravities that could be used. Although several types of movable-bed tracer materials were available at WES, previous investigations (Giles and Chatham 1974, Bottin and Chatham 1975) indicated that crushed coal tracer more nearly represented the movement of prototype sand. Therefore, quantities of crushed coal (specific gravity = 1.30; median diameter, D_{50} = 0.42 - 0.59 mm) were selected for use as a tracer material throughout the model investigation.

3 Test Conditions and Procedures

Selection of Test Conditions

Still-water level

Still-water levels (swl's) for wave action models are selected so that various wave-induced phenomena that are dependent on water depths are accurately reproduced in the model. These phenomena include refraction of waves in the project area, overtopping of harbor structures by waves, reflection of wave energy from various structures, and transmission of wave energy through porous structures.

In most cases, it is desirable to select a model swl that closely approximates the higher water stages which normally occur in the prototype for the following reasons:

a. The maximum amount of wave energy reaching a coastal area normally occurs during the higher water phase of the local tidal cycle.

b. Most storms moving onshore are characteristically accompanied by a higher water level due to wind, tide, and storm surge.

c. The selection of a high swl helps minimize model scale effects due to viscous bottom friction.

d. When a high swl is selected, a model investigation tends to yield more conservative results.

Swl's of +1.0, +1.5, and +2.1 m (+3.2, +5.0, and +7.0 ft) were selected by NPA for use during testing of the St. Paul model. The lower value (+1.0 m (+3.2 ft)) represents mean higher high water (mhhw) and was used while obtaining wave-induced current pattern and magnitudes and sediment tracer patterns and subsequent deposits in the vicinity of the harbor. The +1.5-m (+5.0-ft) value represents mhhw with a 0.5-m (1.8-ft) rise

in local water level due to atmospheric pressure depression, storm surge, and wave setup combined and was used while obtaining wave height data in the harbor and vicinity. The higher value (+2.1 m (+7.0 ft)) was used while obtaining wave height data in the harbor vicinity and while securing wave-induced current patterns, magnitudes, sediment tracer patterns, and subsequent deposits seaward of the main breakwater. This value was estimated at the harbor based on observations made in the prototype during storm wave conditions.

Factors influencing selection of test wave characteristics

In planning the testing program for a model investigation of harbor wave-action problems, it is necessary to select heights, periods, and directions for the test waves that will allow a realistic test of the proposed improvement plans and an accurate evaluation of the elements of the various proposals. Surface-wind waves are generated primarily by the interactions between tangential stresses of wind flowing over water, resonance between the water surface and atmospheric turbulence, and interactions between individual wave components. The height and period of the maximum significant wave that can be generated by a given storm depend on the wind speed, the length of time that wind of a given speed continues to blow, and the distance over water (fetch) that the wind blows. Selection of test wave conditions entails evaluation of such factors as:

a. Fetch and decay distances (the latter being the distance over which waves travel after leaving the generating area) for various directions from which waves can approach the problem area.

b. Frequency of occurrence and duration of storm winds from the different directions.

c. Alignment, size, and relative geographic position of the navigation structures.

d. Alignments, lengths, and locations of the various reflecting surfaces in the area.

e. Refraction of waves caused by differentials in depth in the area seaward of the site, which may create either a concentration or a diffusion of wave energy.

Wave refraction

When waves move into water of gradually decreasing depth, transformations take place in all wave characteristics except wave period (to the first order of approximation). The most important transformations with respect to selection of test wave characteristics are the changes in wave height and direction of travel due to the phenomenon referred to as wave refraction.

During the previous model investigation (Bottin and Mize 1988), the change in wave height and direction at St. Paul Harbor was determined by using the numerical Regional Coastal Processes Wave Transformation Model (RCPWAVE) developed by Ebersole (1985). This model predicts the transformation of monochromatic waves over complex bathymetry and includes refractive and diffractive effects. During the previous study (Bottin and Mize 1988), refraction and shoaling coefficients and shallow-water directions were obtained at St. Paul Harbor for various wave periods from five deepwater wave directions (west-northwest counterclockwise through south-southwest). A summary of the refraction and shoaling analysis is shown in Table 1. The following test directions (deepwater direction and corresponding shallow-water direction) also were selected for use during model testing based on the analysis.

Test Directions

Deepwater Direction, Azimuth, deg	Selected Shallow-Water Test Direction, Azimuth, deg
West-northwest, 292.5	269
West, 270	259
West-southwest, 247.5	245
Southwest, 225	233
South-southwest, 202.5	231

Prototype wave data

Measured prototype data covering a sufficiently long duration from which to base a comprehensive statistical analysis of wave conditions were unavailable for the St. Paul Harbor area. However, in the previous model investigation (Bottin and Mize 1988), statistical deepwater wave hindcast data representative of this area were obtained from the Coastal Engineering Research Center (CERC) Wave Information Studies (WIS). Additional information on WIS may be obtained from Corson (1985). Deepwater wave data at the site are summarized in Table 2. These data were converted to shallow-water values by application of refraction and shoaling coefficients and are shown in Table 3.

Selection of test waves

After a review of the data obtained during the previous model investigation (Bottin and Mize 1988) and due to limited time and funds for the St. Paul Harbor model investigation, NPA initially selected test waves from only the west (259-deg) direction. Test results from this direction indicated it was the most critical with respect to wave heights,

wave-induced current patterns and magnitudes, and sediment tracer patterns at the harbor. Limited tests were conducted, however, for test waves from west-northwest (269 deg) for data comparison. Characteristics of test waves used in the model are shown in the following tabulation.

Selected Test Waves[1]

Period, sec	Height, m (ft)
6	2.1 (7) 3.0 (10)
8	3.0 (10)
10	3.0 (10) 5.8 (19)
12	4.9 (16) 5.8 (19)
14	4.9 (16)
16	4.4 (14.4) 4.7 (15.3) 4.9 (16.2) 5.2 (17) 5.8 (19)
20	4.3 (14)

[1] Incident wave conditions generated at approximate location of wave generator in the model.

Unidirectional wave spectra were generated based on Joint North Sea Wave Project (JONSWAP) parameters for the selected test waves and used throughout the model investigation. Plots of a typical wave spectra are shown in Figure 6. The solid line represents the desired spectra while the dashed line represents the spectra reproduced in the model. A generic JONSWAP gamma function of 3.3 was used to determine the spread of the spectra. The larger the gamma value, the sharper the peak in the energy distribution curve. A typical wave train time series is shown in Figure 7, which depicts water surface elevation (η) versus time. Selected test waves were defined by significant wave height, the average height of the highest one-third of the waves or H_s. In deepwater, H_s is very similar to H_{mo} (energy based wave) where $H_{mo} = 4\,(E)^{1/2}$, and E equals total energy in the spectra, which is obtained by integrating the energy density spectra over the frequency range.

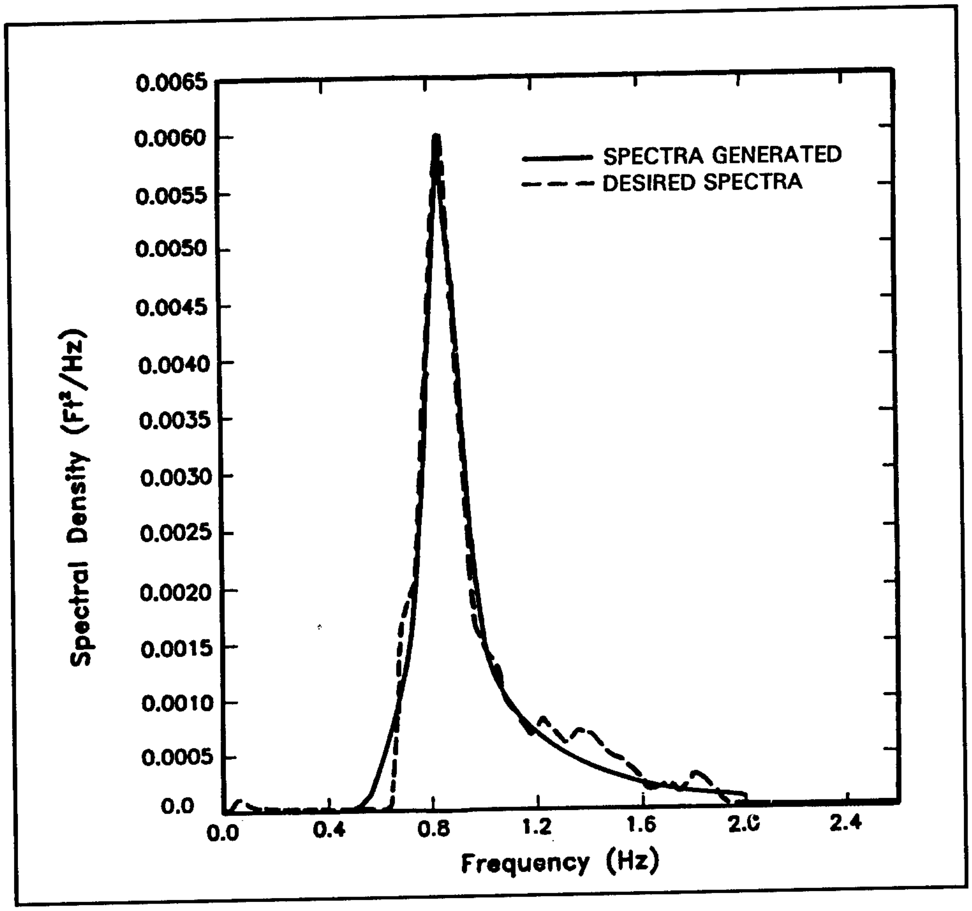

Figure 6. Typical energy density vs. frequency plots (model terms) for a wave spectra; 12-sec, 4.9-m (16-ft) test waves

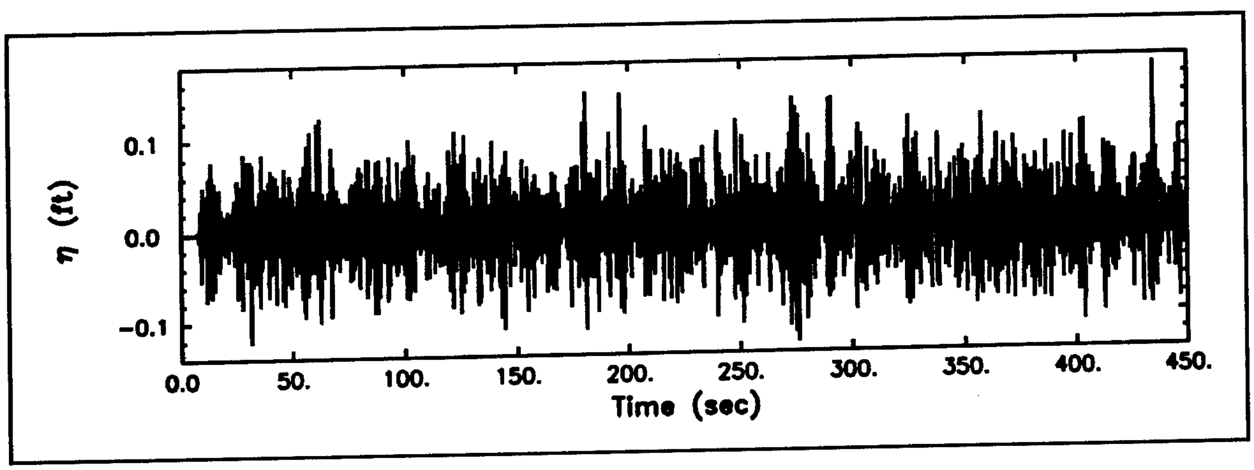

Figure 7. Typical wave train time series, 12-sec, 4.9-m (16-ft) test waves

Analysis of Model Data

Relative merits of the various plans tested were evaluated by:

a. Comparison of wave heights at selected locations in the model.

b. Comparison of wave-induced current patterns and magnitudes.

c. Comparison of sediment tracer movement and subsequent deposits.

d. Visual observations and wave pattern photographs.

In the wave-height data analysis, the average height of the highest one-third of the waves (H_s), recorded at each gauge location, was computed. All wave heights then were adjusted by application of Keulegan's equation[1] to compensate for excessive model wave height attenuation due to viscous bottom friction. From this equation, reduction of model wave heights (relative to the prototype) can be calculated as a function of water depth, width of wave front, wave period, water viscosity, and distance of wave travel, and the model data can be corrected and converted to their prototype equivalents.

[1] G. H. Keulegan, 1950, "The Gradual Damping of a Progressive Oscillatory Wave with Distance in a Prismatic Rectangular Channel," Unpublished data, National Bureau of Standards, Washington, DC, prepared at request of Director, WES, Vicksburg, MS, by Letter of 2 May 1950.

4 Tests and Results

Tests

Existing conditions

Prior to testing of the various improvement plans, comprehensive tests were conducted for existing conditions (Plate 1). Wave height data were obtained in the harbor and/or seaward of the main breakwater for the selected test waves listed on page 21. Sediment tracer patterns, wave-induced current patterns and magnitudes, and wave-pattern photographs were also secured in the harbor and seaward of the main breakwater for representative test waves.

Improvement plans

Proposed improvement plans consisted of the installation of submerged reefs seaward of the existing main breakwater, deepening of an entrance channel, and construction of a maneuvering area both with, and without, a wave dissipating spending beach inside the existing harbor. Wave heights, sediment tracer patterns, wave-induced current patterns and magnitudes, and wave patterns were obtained for representative test waves for 12 test plan configurations. Some of the plans involving the spending beach inside the harbor were constructed expeditiously using gravel to aid in determining the optimum layout for the final test plan. Brief descriptions of the improvement plans are presented in the following subparagraphs, and dimensional details are shown in Plates 2 through 9. Detailed cross sections of the proposed reefs may be found in Ward (1996).

a. Plan 1 (Plate 2) consisted of the installation of three parallel, submerged reefs seaward of the main breakwater. The reefs were constructed with 7,260- to 9,070-kg (8- to 10-ton) stones at el of -2.4 m (-8 ft) with side slopes of 1V:1.5H. They were 274 m (900 ft) in length. The shoreward crest of the inner reef structure was 52 m (170 ft) from the toe of the existing main breakwater. The crest

widths of the reefs were 6.1 m (20 ft), and a distance of 21.3 m (70 ft) separated the reef structures at their crests.

b. Plan 2 (Plate 3) involved the elements of Plan 1, but the innermost reef was removed and the area between the two outermost reefs were filled with 7,260- to 9,070-kg (8- to 10-ton) stone to el -2.4 m (-8 ft). This resulted in a single reef with crest width of 33.5 m (110 ft).

c. Plan 3 (Plate 3) entailed the single reef of Plan 2 with a 152-m (500-ft) northerly extension resulting in a structure length of 427 m (1,400 ft).

d. Plan 4 (Plate 3) included the single reef of Plan 2 with a 122-m (400-ft) northerly extension resulting in a structure length of 396 m (1,300 ft).

e. Plan 5 (Plate 4) involved dredging of a 76-m-wide (250-ft-wide) approach channel, an entrance channel, and a maneuvering area inside the harbor. The depths of these improvements were -9.8 m (-32 ft). In addition, the plan included three parallel, submerged reefs installed seaward of the main breakwater. The reef structures were constructed with 455- to 3,630-kg (1,000- to 8,000-lb) stone at el -3.7 m (-12 ft) with side slopes of 1V:1.5H. They were 396 m (1,300 ft) in length. The shoreward crest of the innermost reef was 52 m (170 ft) from the toe of the existing main breakwater. The crest widths of the reefs were 6.1 m (20 ft), and the crests were 21.3 m (70 ft) apart. The reefs were placed on bedding stone that ranged from 70 to 225 kg (150 to 500 lb).

f. Plan 6 (Plate 5) consisted of the elements of Plan 5 with an expeditiously constructed wave dissipating spending beach installed inside the harbor. The side slopes of the spending beach were 1V:10H.

g. Plan 7 (Plate 5) involved the elements of Plan 5 with an expeditiously constructed wave dissipataing spending beach installed inside the harbor with side slopes of 1V:5H.

h. Plan 8 (Plate 6) included the elements of Plan 5 with an expeditiously constructed wave dissipating spending beach installed inside the harbor. Side slopes of the spending beach were 1V:5H on its seaward face and 1V:10H on its landside face.

i. Plan 9 (Plate 6) consisted of the elements of Plan 5 with the wave dissipating spending beach of Plan 8 inside the harbor, but reefs were reduced in length by 15.2 m (50 ft) on their southern ends resulting in 380-m-long (1,250-ft-long) reef structures.

j. Plan 10 (Plate 7) entailed the deepened entrance channels and maneuvering area of Plan 5 with the 380-m-long (1,250-ft-long) reefs of Plan 9.

k. Plan 11 (Plate 8) consisted of the deepened channels and manueuvering area of Plan 5 and the 380-m-long (1,250-ft-long) reefs of Plan 5. In addition, the plan included a wave dissipating spending beach inside the harbor. The seaward face of the spending beach had side slopes of 1V:5H and was armored with 455-kg (1,000-lb) stone from its toe to el +1.5 m (+5.0 ft). The landside face of the spending beach had 1V:10H side slopes from its toe (approximately the -1.5 m (-5 ft) el) to 0.0 and 1V:5H side slopes from 0.0 to a +3.7-m (+12-ft) el. The 1V:5H side slope was armored with 455-kg (1,000-lb) stone to an el of +1.5 m (+5.0 ft) while the 1V:10H slope was armored with 46-kg (100-lb) stone.

l. Plan 12 (Plate 9) entailed the elements of Plan 11 with a spur that originated 76 m (250 ft) landward of the head of the detached breakwater. The spur was 120 m (400 ft) in length and was armored with 3,630- to 5,440-kg (4- to 6-ton) stone. It had a crest el of 0.0, a crest width of 3 m (10 ft), and 1V:1.5H side slopes.

Wave height tests and wave patterns

Wave height tests were obtained for the various improvement plans for representative test waves listed in Chapter 3. Tests involving certain proposed plans were limited to the most critical swl (i.e., +2.1 m (+7.0 ft)). The most promising improvement plans were tested comprehensively for waves for the +1.5- and +2.1-m (+5.0- and +7.0-ft) swl's. Wave gauge locations are shown in the referenced plates.

Wave-induced current patterns and magnitudes

Wave-induced current patterns and magnitudes were obtained for selected improvement plans for representative test waves. Currents were obtained in the harbor using the +1.0-m (+3.2-ft) swl, while those seaward of the main breakwater were obtained using the +2.1-m (+7.0-ft) swl. These tests were conducted by timing the progress of a dye tracer relative to a known distance on the model surface at selected locations in the model.

Sediment tracer tests

Sediment tracer tests were conducted for selected improvement plans using representative test waves. Tracer material was introduced into the model along the shoreline north of the harbor and/or seaward of the main breakwater to determine sediment tracer patterns and subsequent deposits.

Swl's of +1.0 and +2.1 m (+3.2 and +7.0 ft) were used during the conduct of tracer tests in the harbor and seaward of the main breakwater, respectively.

Test Results

In analyzing test results, the relative merits of various improvement plans were based on measured wave heights in the harbor. Further evaluation was based on wave-induced current patterns and magnitudes and the movement of sediment tracer material and subsequent deposits. Model wave heights (significant wave heights or H_s) were tabulated to show measured values at selected locations. Wave-induced current patterns and magnitudes and sediment tracer patterns and subsequent deposits were shown in photographs. Arrows were superimposed onto these photographs to define direction of movement.

Existing conditions

Results of wave height tests for existing conditions are presented in Table 4 for test waves from west with the +1.5- and +2.1-m (+5.0- and +7.0-ft) swl's. For the 1.5-m (+5.0-ft) swl, maximum wave heights[1] were 4.9 m (16.1 ft) immediately seaward of the main breakwater (gauge 15) for 12-sec, 5.8-m (19-ft) test waves; 1.7 m (5.6 ft) in the harbor entrance (gauge 2) for 16-sec, 5.8-m (19-ft) test waves; 1.6 m (5.2 ft) along the dock in the lee of the main breakwater (gauge 3) for 16-sec, 5.8-m (19-ft) test waves; and 0.6 m (2.0 ft) at the TDX Dock (gauge 9) for 14-sec, 4.9-m (16-ft) test waves. With the +2.1-m (+7.0-ft) swl, maximum wave heights were 6.0 m (19.6 ft) immediately seaward of the main breakwater (gauge 17) for 10-sec, 5.8-m (19-ft) test waves; 2.4 m (7.9 ft) in the harbor entrance (gauge 2) for 20-sec, 4.3-m (14-ft) test waves; 1.7 m (5.7 ft) along the dock in the lee of the main breakwater (gauge 3) for 20-sec, 4.3-m (14-ft) test waves; and 0.8 m (2.7 ft) at the TDX Dock (gauge 9) for 16-sec, 5.8-m (19-ft) test waves. Limited wave height measurements were obtained in the area immediately north of the head of the main breakwater (gauge 13); however, maximum wave heights obtained at this location were 5.0 m (16.4 ft) for 20-sec, 4.3-m (14-ft) test waves with the +2.1-m (+7.0-ft) swl.

Wave-induced current patterns and magnitudes obtained in the harbor for existing conditions for representative test waves from west with the +1.0-m (+3.2-ft) swl are shown in Photos 1 through 6. Maximum velocities obtained at various locations were as follows:

1 Refers to maximum significant wave heights throughout report.

Location	Maximum velocity, mps (fps)	Test Wave	
		Period, sec	Height, m (ft)
Shoreline northwest of detached breakwater	3.0 (10)	20	4.3 (14)
Area north of detached breakwater	2.4 (7.9)	12	4.9 (16)
Opening between shoreline and detached breakwater	2.7 (9)	20	4.3 (14)
Shoreline along boulder spit inside harbor	2.6 (8.5)	20	4.3 (14)
Area along TDX Dock	1.4 (4.7)	20	4.3 (14)
Area along docks in lee of main breakwater	1.4 (4.6)	20	4.3 (14)
Area along head of main breakwater	1.7 (5.7)	12	4.9 (16)

In general, currents moved southerly along the boulder spit to the shoreward end of the detached breakwater where they split. Some currents moved westerly along the seaward side of the detached breakwater, across the entrance, and offshore adjacent to the head of the main breakwater. Currents also moved into the harbor through the opening between the shoreward end of the detached breakwater and the shoreline. Once inside the harbor, currents moved in a clockwise direction and exited through the main harbor entrance. Typical wave patterns for existing conditions for the +1.0-m (+3.2-ft) swl also are shown in Photos 1 through 6.

The placement of tracer material prior to sediment tracer tests is shown in Photo 7 for existing conditions for the +1.0-m (+3.2-ft) swl. The general movement of tracer material and subsequent deposits for representative test waves from west are shown in Photos 8 through 12. Tests for this swl were conducted in a series (i.e., the resulting deposits for test 1 were subjected to waves for test 2, etc). In general, sediment moved southerly along the boulder spit and some material migrated into the harbor through the opening between the detached breakwater and the shoreline. Some material also moved westerly along the seaside of the detached breakwater and migrated seaward across the entrance.

Wave-induced current patterns and magnitudes obtained seaward of the main breakwater for existing conditions with the +2.1-m (+7.0-ft) swl are shown in Photos 13 through 15 for 16- and 20-sec test waves from west. Maximum velocities of 0.8 mps (2.6 fps) were obtained for 16-sec, 4.4-m (14.4-ft) test waves. For the conditions tested, some currents moved northerly and some moved southerly. At some locations currents moved toward the breakwater, while at other locations currents moved seaward away from the structure. Typical wave patterns for existing conditions for the +2.1-m (+7.0-ft) swl also are shown in Photos 13 through 15.

The placement of tracer material seaward of the main breakwater prior to sediment tracer tests is shown in Photo 16 for existing conditions with the +2.1-m (+7.0-ft) swl. The general movement of tracer material and subsequent deposits for 16- and 20-sec test waves from west are shown in Photos 17 through 19. Tracer material tended to move toward the main breakwater and was deposited parallel to the structure. Some material then migrated to the north and some moved toward the south. Only slight deposits occurred in the harbor entrance.

Improvement plans

Wave-induced current patterns and magnitudes obtained seaward of the main breakwater for Plan 1 with the +2.1-m (+7.0-ft) swl are shown in Photos 20 through 22 for 16- and 20-sec test waves from west. Maximum velocities of 0.7 mps (2.3 fps) were obtained for 20-sec, 14-ft test waves. There was little current movement in the lee of the submerged reefs for the conditions tested. In other locations, some currents moved northerly and some moved southerly. Currents seaward of the reefs moved toward the structures at some locations, while at other locations, they moved seaward away from the reefs. Typical wave patterns for Plan 1 also are shown in Photos 20 through 22 for the +2.1-m (+7.0-ft) swl.

The general movement of tracer material and subsequent deposits for 16- and 20-sec test waves from west with Plan 1 installed are shown in Photos 23 through 25 for the +2.1-m (+7.0-ft) swl. Sediment seaward of the submerged reefs migrated toward the structures. Tracer material in the vicinity of the northern portion of the reefs moved northerly, and material around the southern portion moved southerly. Sediment initially placed between the reefs and the main breakwater reoriented itself settling parallel to the structures. Slight deposits occurred in the harbor entrance.

Wave-induced current patterns and magnitudes secured seaward of the main breakwater for Plan 2 with the +2.1-m (+7.0-ft) swl are shown in Photos 26 through 28 for 16- and 20-sec test waves from west. Maximum velocities of 0.7 m (2.3 ft) were obtained for 16-sec, 19-ft test waves. There was little current movement in the lee of the submerged reef. In other locations, some currents moved northerly and some moved southerly. Currents seaward of the reef moved toward the structure at some locations, while at others, they moved seaward away from the reef. Typical wave patterns for Plan 2 are also shown in Photos 26 through 28 for the +2.1-m (+7.0-ft) swl.

The general movement of tracer material and subsequent deposits for 16- and 20-sec test waves from west with Plan 2 installed are shown in Photos 29 through 31 for the +2.1-m (+7.0-ft) swl. Sediment seaward of the submeged reef migrated toward the structure. Tracer material in the vicinity of the northern portion of the reef moved northerly, and that around the southern portion moved southerly. Sediment initially placed

between the reef and the main breakwater tended to reorient itself parallel to the structures. Only slight deposits occurred in the harbor entrance.

Wave height test results for Plans 2 through 4 are presented in Table 5 for 16- and 20-sec test waves from west for the +2.1-m (+7.0-ft) swl. Maximum wave heights were 4.2, 3.8, and 3.9 m (13.7, 12.6, and 12.8 ft) between the main breakwater and the reef (gauges 15 to 17); 4.6, 4.3, and 4.4 m (15.0, 14.0, and 14.4 ft) in the area immediately north of the head of the main breakwater (gauge 13); 2.3, 2.0, and 2.1 m (7.5, 6.7, and 6.9 ft) in the harbor entrance (gauge 2); 1.65, 1.6, and 1.65 m (5.4, 5.3, and 5.4 ft) along the dock in the lee of the main breakwater (gauge 3); and 0.76, 0.73, and 0.73 m (2.5, 2.4, and 2.4 ft) at the TDX Dock (gauge 9) for Plans 2 through 4, respectively.

Results of wave height tests for Plans 5 through 9 are presented in Table 6 for 16- and 20-sec test waves from west for the +2.1-m (+7.0-ft) swl. Maximum wave heights were 4.08, 4.0, 4.0, 4.05, and 4.0 m (13.4, 13.1, 13.1, 13.3, and 13.1 ft) between the main breakwater and the reefs (gauges 15 to 17); 4.6, 4.54, 4.51, 4.54, and 4.54 m (15.0, 14.9, 14.8, 14.9, and 14.9 ft) in the channel immediately north of the head of the main breakwater (gauge 13); 1.7, 1.55, 1.6, 1.55, and 1.55 m (5.5, 5.1, 5.2, 5.1, and 5.1 ft) in the harbor entrance (gauge 2); 1.6, 1.55, 1.64, 1.6, and 1.55 m (5.2, 5.1, 5.4, 5.2, and 5.1 ft) along the dock in the lee of the main breakwater (gauge 3); and 0.88, 0.67, 0.67, 0.67, and 0.67 m (2.9, 2.2, 2.2, 2.2, and 2.2 ft) at the TDX Dock (gauge 9) for Plans 5 through 9, respectively.

Wave height test results with Plan 10 installed in the model are presented in Table 7 for test waves from west with the +1.5- and +2.1-m (+5.0- and +7.0-ft) swl's. For the +1.5-m (+5.0-ft) swl, maximum wave heights were 4.2 m (13.7 ft) between the main breakwater and the reefs (gauges 15 to 17) for 12-sec, 5.8-m (19-ft) test waves; 4.1 m (13.4 ft) in the channel immediately north of the head of the main breakwater (gauge 13) for 16-sec, 5.8-m (19-ft) test waves; 1.5 m (4.9 ft) in the harbor entrance (gauge 2) for 12- and 16-sec, 5.8-m (19-ft) test waves; 1.4 m (4.5 ft) along the dock in the lee of the main breakwater (gauge 3) for 16-sec, 5.8-m (19-ft) test waves; and 0.8 m (2.6 ft) at the TDX Dock (gauge 9) for 12-sec, 5.8-m (19-ft) and 14-sec, 4.9-m (16-ft) test waves. With the +2.1-m (+7.0-ft) swl, maximum wave heights were 5.0 m (16.4 ft) between the main breakwater and the reefs (gauges 15 to 17) for 10-sec, 5.8-m (19-ft) test waves; 4.6 m (15.2 ft) in the channel immediately north of the head of the main breakwater (gauge 13) for 16-sec, 5.8-m (19-ft) test waves; 1.8 m (5.9 ft) in the harbor entrance (gauge 2) for 20-sec, 4.3-m (14-ft) test waves; 1.6 m (5.4 ft) along the dock in the lee of the main breakwater (gauge 3) for 20-sec, 4.3-m (14-ft) test waves; and 1.0 m (3.2 ft) at the TDX Dock (gauge 9) for 20-sec, 4.3-m (14-ft) test waves.

Wave-induced current patterns and magnitudes obtained in the harbor for Plan 10 for representative test waves from west with the +1.0-m (+3.2-ft) swl are shown in Photos 32 through 37. Maximum velocities obtained at various locations were as follows:

Location	Maximum velocity, mps (fps)	Test Wave(s)	
		Period, sec	Height, m (ft)
Shoreline northwest of detached breakwater	2.4 (7.8)	10	5.8 (19)
Area north of detached breakwater	1.7 (5.5)	20	4.3 (14)
Opening between shoreline and detached breakwater	2.2 (7.1)	8 10 16 20	3.0 (10) 5.8 (19) 5.8 (19) 4.3 (14)
Shoreline along boulder spit inside harbor	2.8 (9.1)	12	4.9 (16)
Area along TDX Dock	1.4 (4.7)	10	5.8 (19)
Area along docks in lee of main breakwater	1.2 (4.0)	12	4.9 (16)
Area along head of main breakwater	1.5 (5.0)	10	5.8 (19)

In general, currents moved southerly along the boulder spit to the shoreward end of the detached breakwater where they split. Some currents moved westerly along the seaward side of the detached breakwater, across the entrance, and offshore adjacent to the head of the main breakwater. Currents also moved into the harbor through the opening between the shoreward end of the detached breakwater and the shoreline. Once inside the harbor, currents moved in a clockwise direction and exited through the main harbor entrance. Typical wave patterns for Plan 10 with the +1.0 m (+3.2 ft) swl also are shown in Photos 32 through 37.

The placement of tracer material prior to sediment tracer tests is shown in Photo 38 for Plan 10 for the +1.0-m (+3.2-ft) swl. The general movement of tracer material and subsequent deposits for representative test waves from west are shown in Photos 39 through 43. In general, sediment moved southerly along the boulder spit and some material migrated into the harbor through the opening between the detached breakwater and the shoreline. Some material also moved westerly along the seaside of the detached breakwater and migrated seaward across the entrance channel.

Results of wave height tests with Plan 11 installed in the model are presented in Table 8 for test waves from west with the +1.5- and +2.1-m (+5.0- and +7.0-ft) swl's. For the +1.5-m (+5.0-ft) swl, maximum wave heights were 4.2 m (13.9 ft) between the main breakwater and the reefs (gauges 15-17) for 12-sec, 5.8-m (19-ft) test waves; 4.1 m (13.6 ft) in the channel immediately north of the head of the main breakwater (gauge 13) for 16-sec, 5.8-m (19-ft) test waves; 1.5 m (5.0 ft) in the harbor entrance

(gauge 2) for 12-sec, 5.8-m (19-ft) test waves; 1.3 m (4.4 ft) along the dock in the lee of the main breakwater (gauge 3) for 16-sec, 5.8-m (19-ft) test waves; and 0.6 m (2.0 ft) at the TDX Dock (gauge 9) for 12-sec, 5.8-m (19 ft) test waves. With the +2.1-m (+7.0-ft) swl, maximum wave heights were 5.0 m (16.4 ft) between the main breakwater and the reefs (gauges 15-17) for 10-sec, 5.8-m (19-ft) test waves; 4.6 m (15.1 ft) in the channel immediately north of the head of the main breakwater (gauge 13) for 16-sec, 5.2-m (17-ft) test waves; 1.65 m (5.4 ft) in the harbor entrance (gauge 2) for 16-sec, 5.2- and 5.8-m (17- and 19-ft) and 20-sec, 4.3-m (14-ft) test waves; 1.62 m (5.3 ft) along the dock in the lee of the main breakwater (gauge 3) for 16-sec, 5.2-m (17-ft) test waves; and 0.7 m (2.3 ft) at the TDX Dock (gauge 9) for 20-sec, 4.3-m (14-ft) test waves.

Wave-induced current patterns and magnitudes obtained in the harbor for Plan 11 for representative test waves from west with the +1.0-m (+3.2-ft) swl are shown in Photos 44 through 49. Maximum velocities obtained at various locations were as follows:

Location	Maximum velocity, mps (fps)	Test Wave	
		Period, sec	Height, m (ft)
Shoreline northwest of detached breakwater	2.5 (8.3)	16	5.8 (19)
Area north of detached breakwater	1.6 (5.4)	12	4.9 (16)
Opening between shoreline and detached breakwater	2.3 (7.7)	16	5.8 (19)
Shoreline along boulder spit inside harbor	2.3 (7.6)	12	4.9 (16)
Area along TDX Dock	1.6 (5.2)	16	5.8 (19)
Area along docks in lee of main breakwater	1.2 (3.9)	10	5.8 (19)
Area along head of main breakwater	1.4 (4.6)	16	5.8 (19)

Currents, in general, moved southerly along the boulder spit to the shoreward end of the detached breakwater where they split. Some currents moved westerly along the seaward side of the detached breakwater, across the entrance, and offshore adjacent to the head of the main breakwater. Currents also moved into the harbor through the opening between the shoreward end of the detached breakwater and the shoreline. Once inside the harbor, currents moved in a clockwise direction and exited through the main harbor entrance. Typical wave patterns for Plan 11 with the +1.0-ft (+3.2-ft) swl, are also shown in Photos 44 through 49 for test waves from west.

The general movement of tracer material and subsequent deposits for representative test waves from west are shown in Photos 50 through 54 for Plan 11 with the +1.0-m (+3.2-ft) swl. In general, sediment moved

southerly along the boulder spit and some material migrated into the harbor through the opening between the detached breakwater and the shoreline. Some material also moved westerly along the seaside of the detached breakwater and migrated seaward across the harbor entrance.

Wave-induced current patterns and magnitudes obtained seaward of the main breakwater for Plan 11 with the +2.1-m (+7.0-ft) swl are shown in Photos 55 through 57 for 16- and 20-sec test waves from west. Maximum velocities of 1.0 mps (3.2 fps) were obtained seaward of the reefs for 16-sec, 5.8-m (19-ft) test waves. There was little current movement in the lee of the submerged reefs. In other locations, some currents moved northerly, while some moved southerly. Currents seaward of the reefs moved toward the structure at some locations and seaward away from the reefs at other locations for various test conditions. Typical wave patterns for Plan 11 for the +2.1-m (+7.0-ft) swl also are shown in Photos 55 through 57 for test waves from west.

The placement of tracer material seaward of the main breakwater prior to sediment tracer tests for Plan 11 for test waves from west is shown in Photo 58 for the +2.1-m (+7.0-ft) swl. The general movement of tracer material and subsequent deposits for 16-and 20-sec test waves from west are shown in Photos 59 through 61. Sediment seaward of the submerged reefs migrated toward the structures. Tracer material in the vicinity of the northern portion of the reefs moved northerly, and that around the southern portion moved southerly. Sediment initially placed between the reefs, and the main breakwater tended to reorient itself parallel to the structures. Only slight deposits occurred in the harbor entrance.

Results of wave height tests for test waves from west-northwest with Plan 11 installed in the model are presented in Table 9 for the +1.5- and +2.1-m (+5.0- and +7.0-ft) swl's. For the +1.5-m (+5.0-ft) swl, maximum wave heights were 4.8 m (15.8 ft) between the main breakwater and the reefs (gauges 15 to 17) for 12-sec, 4.9-m (16-ft) test waves; 4.8 m (15.6 ft) in the channel immediately north of the head of the main breakwater (gauge 13) for 16-sec, 5.8-m (19-ft) test waves; 1.7 m (5.5 ft) in the harbor entrance (gauge 2) for 12-sec, 5.8-m (19 ft) test waves; 1.3 m (4.4 ft) along the dock in the lee of the main breakwater (gauge 3) for 16-sec, 5.8-m (19-ft) test waves; and 0.7 m (2.3 ft) at the TDX Dock (gauge 9) for 12-sec, 5.8-m (19-ft) test waves. With the +2.1-m (+7.0-ft) swl, maximum wave heights were 5.8 m (19.1 ft) between the main breakwater and the reefs (gauges 15 to 17) for 10-sec, 5.8-m (19-ft) test waves; 4.6 m (15.1 ft) in the channel immediately north of the head of the main breakwater (gauge 13) for 16-sec, 5.8-m (19-ft) test waves; 1.8 m (5.8 ft) in the harbor entrance (gauge 2) for 16-sec, 5.8-m (19-ft) test waves; 1.5 m (5.0-ft) along the dock in the lee of the main breakwater (gauge 3) for 16-sec, 5.2-m (17-ft) and 20-sec, 4.3-m (14-ft) test waves; and 0.7 m (2.3 ft) at the TDX Dock (gauge 9) for several of the test waves.

Wave-induced current patterns and magnitudes obtained seaward of the main breakwater for Plan 11 for 16- and 20-sec test waves from west-northwest with the +2.1-m (+7.0-ft) swl are shown in Photos 62 through 64. Maximum velocities obtained were 1.6 mps (5.1 fps) along the shoreline immediately south of the structures; and 0.5 mps (1.5 fps) in the lee of the submerged reefs. In some locations, currents moved northerly while at others they some moved southerly. Currents seaward of the reefs moved toward the structure at some locations, and seaward away from the structures at other locations for the various test conditions. Typical wave patterns for Plan 11 for the +2.1-m (+7.0-ft) swl also are shown in Photos 62 through 64 for test waves from west-northwest.

The placement of tracer material seaward of the main breakwater prior to sediment tracer tests for Plan 11 for test waves from west-northwest is shown in Photo 65 for the +2.1-m (+7.0-ft) swl. The general movement of tracer material and subsequent deposits for 16- and 20-sec test waves from west-northwest are shown in Photos 66 through 68. Sediment seaward of the submerged reefs migrated toward the structures. Tracer material in the vicinity of the northern portion of the reefs migrated northerly, and that around the southern portion moved southerly. Sediment initially placed between the reefs and the main breakwater tended to reorient itself parallel to the structures. Only slight deposits occurred in the harbor entrance.

Results of wave height tests for representative waves from west with Plan 12 installed in the model are presented in Table 10 for the +2.1-m (+7.0-ft) swl. Maximum wave heights were 4.2 m (13.8 ft) between the main breakwater and the reefs (gauges 15-17) for 12-sec, 5.8-m (19-ft) test waves; 4.8 m (15.9 ft) in the channel immediately north of the head of the main breakwater (gauge 13) for 20-sec, 4.3-m (14-ft) test waves; 1.7 m (5.6 ft) in the harbor entrance (gauge 2) for 16-sec, 5.8-m (19-ft) test waves; 1.55 m (5.1 ft) along the dock in the lee of the main breakwater (gauge 3) for 16-sec, 5.8-m (19 ft) test waves; and 0.6 m (2.1 ft) at the TDX Dock (gauge 9) for 16-sec, 4.4-m (14.4-ft) and 20-sec, 4.3-m (14-ft) test waves.

Wave-induced current patterns and magnitudes obtained in the harbor for Plan 12 for representative test waves from west with the +1.0-m (+3.2-ft) swl are shown in Photos 69 through 72. Maximum velocities obtained at various locations were as follows:

Location	Maximum velocity, mps (fps)	Test Wave(s)	
		Period, sec	Height, m (ft)
Shoreline northwest of detached breakwater	2.4 (8.0)	12	4.9 (16)
Area north of detached breakwater	1.4 (4.6)	12	4.9 (16)
Opening between shoreline and detached breakwater	2.2 (7.1)	8 12 16 20	3.0 (10) 4.9 (16) 5.8 (19) 4.3 (14)
Shoreline along boulder spit inside harbor	2.5 (8.3)	12	4.9 (16)
Area along TDX Dock	1.4 (4.6)	12 20	4.9 (16) 4.3 (14)
Area along docks in lee of main breakwater	1.3 (4.4)	16	5.8 (19)
Area along head of main breakwater	1.2 (4.0)	16 20	5.8 (19) 4.3 (14)

In general, currents moved southerly along the boulder spit to the shoreward end of the detached breakwater where they split. Some currents moved along the seaward side of the detached breakwater and were deflected northerly by the breakwater spur. They moved across the northern portion of the entrance channel and then seaward. Currents also moved into the harbor through the opening between the shoreward end of the detached breakwater and the shoreline. Once inside the harbor, currents moved in a clockwise direction and exited through the main harbor entrance. Typical wave patterns for Plan 12 for test waves from west with the +1.0 m (+3.2 ft) swl also are shown in Photos 69 through 72.

The placement of tracer material prior to sediment tracer tests is shown in Photo 73 for Plan 12 for the +1.0-m (+3.2-ft) swl. The general movement of tracer material and subsequent deposits for representative test waves from west are shown in Photos 74 through 78. In general, sediment moved southerly along the boulder spit and some material migrated into the harbor through the opening between the detached breakwater and the shoreline. Some material also moved westerly along the seaside of the detached breakwater and were deflected northerly by the breakwater spur. Deposits occurred only in the northerly portion of the entrance channel.

Discussion of Test Results

Results of wave height tests for existing conditions revealed that wave heights of 1.7 m (5.7 ft) will occur along the dock (gauge 3) in the lee of the main breakwater, and wave heights of 0.8 m (2.7 ft) will occur at the TDX Dock (gauge 9) during periods of severe wave attack with high-tide

conditions. Tests also indicated that wave heights of almost 2.4 m (8.0 ft) will occur in the harbor entrance (gauge 2) during storm conditions.

Wave-induced current pattern and magnitude tests for existing conditions indicated that currents will move southerly along the boulder spit north of the harbor. Some will enter the harbor between the opening at the shoreward end of the detached breakwater and the shoreline. These currents will move in a clockwise direction in the harbor and exit through the entrance. Other currents will move westerly along the north side of the detached breakwater, then seaward across the harbor entrance. Maximum velocities of 2.6 mps (8.5 fps) will occur along the shoreline inside the harbor during periods of severe storm wave attack.

Sediment tracer patterns and subsequent deposits for existing conditions revealed southerly sediment movement along the boulder spit toward the harbor for the conditions tested. Some material migrated into the harbor through the opening between the detached breakwater and the shoreline. Other material moved westerly along the seaside of the detached breakwater and migrated toward the harbor entrance. Postconstruction bathymetric surveys at St. Paul Harbor validate these sediment movement patterns. Shoaling of the harbor has been observed as well as a shoal formation on the seaside of the detached breakwater extending to the entrance.

Comparisons of current patterns and magnitudes and sediment tracer patterns and deposits seaward of the main breakwater for existing conditions and the initial submerged reef plans (Plans 1 and 2) revealed the structures would have little impact. Maximum velocities of 0.8 mps (2.6 fps) were obtained for existing conditions with maximum velocities of 0.7 mps (2.3 fps) obtained for both Plans 1 and 2 seaward of the main breakwater for the conditions tested. Depending on location, currents moved northerly, southerly, seaward, and toward the main breakwater for existing conditions and the improvement plans. Sediment tracer material, generally, migrated toward the main breakwater for both existing conditions and the initial improvement plans. Sediment movement in the vicinity of the northern portion of the breakwaters moved northerly and that in the southern portion of the breakwaters moved southerly. Additionally, sediment tended to reorient itself parallel to the main breakwater and only slight deposits occurred in the entrance for existing conditions and the improvement plans.

Test results indicated that extending the initial lengths of the submerged reefs to the north (Plans 3 and 4) would result in reduced wave heights in the approach channel (gauge 13) and entrance channel (gauge 2) into the harbor. The 152-m (500-ft) extension (Plan 3) protruded into the proposed approach channel slightly and may interfere with navigation; therefore, the 122-m (400-ft) extension (Plan 4) was selected as optimal. Visual observations revealed that the extended reefs tended also to dissipate a rip current that was observed in the channel for existing conditions. Maximum wave heights were reduced by 0.6 m (2.0 ft) in the approach

channel north of the main breakwater head (gauge 13) and 0.3 m (1.0 ft) in the entrance channel (gauge 2) with Plan 4 installed when compared with results obtained for existing conditions. These reduced wave heights as well as the absence of the rip current in the channel should result in improved navigation conditions.

Initial wave height tests for the deepened entrance channel and maneuvering area and the 396-m-long (1,300-ft-long) submerged reefs of Plan 5 revealed that wave heights in the approach and entrance channels and along the docks in the lee of the main breakwater were less than those obtained for existing conditions. However, wave heights along the TDX Dock in the harbor were slightly increased. In an effort to reduce wave height values at this location, expeditiously constructed wave dissipating spending beaches were installed. Wave height tests for the expeditiously constructed wave dissipating spending beach alternatives allowed for quick comparisons of wave data for various spending beach configurations and side slopes. The final spending beach configuration and side slopes selected for testing were determined through these expedited tests. While the expeditiously constructed spending beach plans were installed, the submerged reefs were reduced in length by 15.2 m (50 ft) on their southern end (Plan 9). Test results indicated this reduction could be made without impacting wave conditions in the harbor.

Results of comprehensive wave height tests with the deepened channel and maneuvering area and the 381-m-long (1,250-ft-long) submerged reefs (Plan 10) revealed that wave heights in the approach and entrance channels and along the docks in the lee of the main breakwater were less than those obtained for existing conditions with the exception of wave heights at the TDX Dock (gauge 9) and inner harbor area (gauge 12). Maximum wave heights at the TDX Dock were 0.8 m (2.7 ft) for existing conditions and 1.0 m (3.2 ft) for Plan 10; and maximum wave heights in the inner harbor were 0.6 and 0.7 m (2.0 and 2.3 ft), respectively, for existing conditions and Plan 10.

The installation of the wave-dissipating spending beach inside the harbor adjacent to the detached breakwater (Plan 11) resulted in decreased wave heights in the harbor. Wave heights along the TDX Dock (gauge 9) were reduced by 0.3 m (0.9 ft) and those in the inner harbor (gauge 12) were reduced by 0.2 m (0.6 ft) when compared to Plan 10 (no spending beach in the harbor). When compared to existing conditions, wave heights throughout the harbor were significantly less for Plan 11. The greatest decrease in wave heights occurred in the proposed maneuvering area (gauge 8) of Plan 11. Maximum wave heights in this area were 0.7 m (2.3 ft) for Plan 11 versus 1.4 m (4.6 ft) for existing conditions at the same location. The wave-dissipating spending beach of Plan 11 appeared to be optimal with respect to wave conditions in the harbor and will result in significant improvement over existing conditions.

Comparisons of wave-induced current patterns and magnitudes for Plan 10 (deepened channel and maneuvering area and 381-m-long (1,250-ft-long) submerged reefs) and Plan 11 (addition of wave-dissipating spending beach) revealed similar results as those obtained for existing conditions. Currents generally moved southerly along the boulder spit to the shoreward end of the detached breakwater where they split. Some currents moved westerly along the seaward side of the detached breakwater, across the entrance, and offshore adjacent to the head of the main breakwater. Currents also moved into the harbor through the opening between the detached breakwater and the shoreline. They then moved in a clockwise direction and exited the harbor through the main entrance. Current magnitudes measured in the harbor also were similar. Velocities were greater for existing conditions than the improvement plans at some locations and at other locations they were less. In general, however, trends in current magnitudes were similar for both existing conditions and the test plans. Current patterns seaward of the main breakwater also were similar for existing conditions and Plan 11. Some currents moved northerly and some moved southerly, and at some locations, currents moved toward the main breakwater while at other locations they moved seaward away from the structure. It was noted that very little current movement occurred in the lee of the submerged reefs of Plan 11. Current magnitudes were variable (greater for existing conditions in some locations and less in others than those obtained for Plan 11). After a review of all wave-induced current patterns and magnitudes obtained for existing conditions and Plans 10 and 11, it was concluded that the installation of the improvement plans should have no adverse impacts on currents in the vicinity of the harbor.

Comparisons of sediment tracer patterns and subsequent deposits for Plan 10 (deepened channel and maneuvering area and 381-m-long (1,250-ft-long) submerged reefs) and Plan 11 (addition of wave-dissipating spending beach) revealed similar results as those obtained for existing conditions. Tests for existing conditions and Plans 10 and 11 revealed southerly sediment movement along the boulder spit toward the harbor. Some material migrated into the harbor through the opening between the detached breakwater and the shoreline. Other material moved westerly along the seaside of the detached breakwater and migrated across the entrance channel. For existing conditons, sediment seaward of the main breakwater tended to initially migrate toward the structure and deposit parallel to the structure. Some material migrated to the north and some toward the south. Only slight deposits occurred in the harbor entrance. For Plans 10 and 11, sediment seaward of the submerged reefs migrated toward the structures. Tracer material in the vicinity of the northern portion of the reefs moved northerly, and material in the southern portion moved southerly. Sediment initially placed between the reefs and the main breakwater tended to reorient itself parallel to the structures. Only slight deposits occured in the harbor entrance. Considering sediment movement patterns and subsequent deposits obtained for existing conditions and Plans 10 and 11, it was concluded that the installation of the improvement plans should have no adverse impacts on sediment movement in the vicinity of the harbor.

A comparison of test results with Plan 11 (deepened channel and maneuvering area, 381-m-long (1,250-ft-long) submerged reefs, and wave-dissipating spending beach) installed for waves from west and west-northwest indicated that maximum wave heights will increase by 0.15 m (0.5 ft) in the harbor entrance and 0.12 m (0.4 ft) in the harbor for the west-northwest direction. Increases in wave heights could be expected, however, since the harbor entrance is more exposed to west-northwest waves. Current pattern and magnitude tests revealed slightly more current activity in the lee of the submerged reefs for waves from west-northwest. Currents ranging from 0.3 to 0.4 mps (1.0 to 1.4 fps) were observed in this area moving in a northerly direction. The results of sediment tracer tests for Plan 11 indicated almost identical sediment movement patterns and subsequent deposits for test waves from west and west-northwest.

Installation of the 120-m-long (400-ft-long) spur on the detached breakwater (Plan 12) revealed that the spur will redirect currents moving westerly along the detached breakwater. As opposed to currents moving seaward across the entrance channel, they moved across the northern edge of the channel. Current patterns and magnitudes throughout the rest of the harbor were similar to conditions obtained without the spur installed. Sediment tracer patterns and subsequent deposits also were deflected northerly to the northern edge of the entrance channel (as opposed to in the channel) by the spur. The spur, therefore, should reduce the shoaling potential of the entrance channel. Wave heights in the existing harbor also were similar with the spur installed when compared to conditions without the spur. Wave heights were slightly less at some locations and slightly greater at others with the spur installed, but maximum wave heights only differed by 0.03 to 0.06 m (0.1 to 0.2 ft).

5 Conclusions

Based on results of the coastal model investigation reported herein, it is concluded that:

a. During periods of severe storm wave activity with extreme high-tide conditions, wave heights in the existing harbor will exceed 1.7 m (5.5 ft) along the dock in the lee of the main breakwater and 0.8 m (2.5 ft) at the TDX Dock.

b. For existing conditions, currents enter the harbor through the opening at the shoreward end of the detached breakwater and move in a clockwise direction exiting through the entrance. Maximum velocities along the shoreline inside the harbor will exceed 2.5 mps (8 fps). Currents also move seaward along the seaside of the detached breakwater across the harbor entrance.

c. For existing conditions, sediment moves southerly along the boulder spit and enters the harbor through the opening at the shoreward end of the detached breakwater. Sediment also moves westerly along the seaside of the detached breakwater toward the harbor entrance.

d. Test results obtained for the initial submerged reefs (Plans 1 and 2) indicated the structures would have no adverse impact on current patterns and magnitudes or sediment tracer patterns and deposits seaward of the main breakwater.

e. An extension of the initial submerged reefs northerly by 122 m (400 ft) in length (Plan 4) will decrease wave heights in the approach and entrance channels and result in improved navigation conditions.

f. A 15.2-m (50-ft) reduction in the length of the submerged reefs (from 396 to 381 m (1,300 to 1,250 ft)) on their southern end (Plan 9) will not increase wave conditions in the harbor.

g. Test results for the deepened channel and maneuvering area and the 381-m-long (1,250-ft-long) submerged reefs of Plan 10 indicated that wave heights would increase at the TDX Dock and the inner harbor area when compared to existing conditions.

h. Installation of the wave-dissipating spending beach in the harbor (Plan 11) with the deepened channel and maneuvering area and the 381-m-long (1,250-ft-long) submerged reefs will result in reduced wave conditions. Wave heights throughout the harbor will be significantly less than those obtained for existing conditions.

i. Installation of Plan 10 (deepened channel and maneuvering area and the 381-m-long (1,250-ft-long) submerged reefs) or Plan 11 (addition of the wave-dissipating spending beach) will have no adverse impact on current patterns and magnitudes and/or sediment patterns and subsequent deposits in the vicinity of the harbor.

j. The 120-m-long (400-ft-long) breakwater spur of Plan 12 will have no adverse impact on wave or current conditions in the harbor. It will, however, redirect sediment movement and subsequent deposits from the entrance channel to the northerly edge of the channel, and thus, reduce the potential for shoaling.

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Table 1
Summary of Refraction and Shoaling Analysis for St. Paul Harbor, Alaska

Deep-Water Direction, deg	Wave Period, sec	Shallow-Water Azimuth, deg[1]	Refraction Coefficient[1]	Shoaling Coefficient[1]	Wave-Height Adjustment Factor
West-northwest (292.5)	6	283.3	0.566	0.965	0.546
	8	275.8	0.569	0.918	0.522
	10	270.6	0.628	0.918	0.577
	12	264.7	0.527	0.944	0.497
	14	262.2	0.574	0.982	0.564
	16	259.4	0.657	1.024	0.673
West (270)	6	268.0	0.954	0.965	0.921
	8	263.9	0.865	0.918	0.794
	10	260.2	0.858	0.918	0.788
	12	256.9	0.892	0.944	0.842
	14	254.0	0.913	0.982	0.897
	16	251.4	0.889	1.024	0.910
West-southwest (247.5)	6	247.6	0.998	0.965	0.963
	8	246.7	1.003	0.918	0.921
	10	245.0	0.966	0.918	0.887
	12	244.0	0.914	0.944	0.863
	14	242.9	0.882	0.982	0.866
	16	242.0	0.855	1.024	0.876
Southwest (225)	6	227.8	0.803	0.965	0.775
	8	231.2	0.723	0.918	0.664
	10	233.5	0.648	0.918	0.595
	12	234.0	0.613	0.944	0.579
	14	235.0	0.591	0.982	0.580
	16	235.8	0.583	1.024	0.597
South-southwest (202.5)	6	224.9	0.554	0.965	0.535
	8	229.7	0.783	0.918	0.719
	10	233.4	0.754	0.918	0.692
	12	233.7	0.442	0.944	0.417
	14	231.7	0.556	0.982	0.546
	16	235.1	0.498	1.024	0.510

[1] At approximate locations of wave generator in model.

Table 2
Estimated Magnitude of Deepwater Waves (Sea and Swell) Approaching St. Paul Harbor from the Directions Indicated

Wave height, ft	Occurrences per Wave Period, sec[1] 4.4-6.0	6.1-8.0	8.1-10.5	10.6-13.3	13.4-15.3	15.4-18.1	>18.2	Total
West-northwest								
0.0-3.3	3	—	1	—	—	—	—	4
3.3-6.6	18	41	108	1	—	—	—	168
6.6-9.8	7	36	137	40	1	—	—	221
9.8-13.1	—	23	41	74	1	—	—	139
13.1-16.4	—	—	20	61	5	—	—	86
16.4-19.7	—	—	8	31	7	1	—	47
19.7-23.0	—	—	1	3	8	—	—	12
23.0-26.2	—	—	—	—	4	1	—	5
26.2-29.5	—	—	—	—	—	—	—	—
29.5-32.8	—	—	—	—	—	1	—	1
>32.8	—	—	—	—	—	1	—	1
Total	**28**	**100**	**316**	**210**	**26**	**4**	—	**684**
West								
0.0-3.3	2	5	10	—	—	—	—	17
3.3-6.6	19	64	124	3	—	—	—	210
6.6-9.8	18	65	220	46	—	—	—	349
9.8-13.1	1	50	101	142	3	—	—	297
13.1-16.4	—	1	51	161	12	—	—	225
16.4-19.7	—	—	29	54	16	1	—	100
19.7-23.0	—	—	2	28	14	—	—	44
23.0-26.2	—	—	—	13	8	—	—	21
26.2-29.5	—	—	—	5	4	1	—	10
29.5-32.8	—	—	—	1	3	—	—	4
>32.8	—	—	—	1	2	1	—	4
Total	**40**	**185**	**537**	**454**	**62**	**3**	—	**1,281**

(Continued)

[1] Occurrences compiled for period 1966-1975. Each occurrence represents a 6-hr duration.

Table 2 (Concluded)

Wave height, ft	Occurrences per Wave Period, sec[1]							
	4.4-6.0	6.1-8.0	8.1-10.5	10.6-13.3	13.4-15.3	15.4-18.1	>18.2	Total
West-southwest								
0.0-3.3	1	2	4	—	—	—	—	7
3.3-6.6	9	50	65	3	—	—	—	127
6.6-9.8	16	81	159	31	1	—	—	288
9.8-13.1	—	48	76	87	—	—	—	211
13.1-16.4	—	3	55	134	4	—	—	196
16.4-19.7	—	—	24	64	23	1	—	112
19.7-23.0	—	—	4	35	20	—	—	59
23.0-26.2	—	—	1	17	10	2	—	30
26.2-29.5	—	—	—	7	4	—	—	11
29.5-32.8	—	—	—	2	1	—	—	3
>32.8	—	—	—	1	—	2	—	3
Total	**26**	**184**	**388**	**381**	**63**	**5**	**—**	**1,047**
Southwest								
0.0-3.3	1	4	1	—	—	—	—	6
3.3-6.6	7	33	51	—	—	—	—	91
6.6-9.8	10	43	121	23	—	—	—	197
9.8-13.1	—	24	66	72	1	—	—	163
13.1-16.4	—	1	50	102	2	—	—	155
16.4-19.7	—	—	19	70	17	—	—	106
19.7-23.0	—	—	5	44	19	—	—	68
23.0-26.2	—	—	1	31	17	1	—	50
26.2-29.5	—	—	—	15	6	2	—	23
29.5-32.8	—	—	—	6	3	1	—	10
>32.8	—	—	—	—	3	—	—	3
Total	**18**	**105**	**314**	**363**	**68**	**4**	**—**	**872**
South-southwest								
0.0-3.3	—	3	—	—	—	—	—	3
3.3-6.6	5	22	58	2	—	—	—	87
6.6-9.8	2	36	106	10	—	—	—	154
9.8-13.1	—	13	52	60	—	—	—	125
13.1-16.4	—	2	25	107	4	—	—	138
16.4-19.7	—	—	25	57	10	—	—	92
19.7-23.0	—	—	11	31	14	—	—	56
23.0-26.2	—	—	1	17	10	—	—	28
26.2-29.5	—	—	—	8	5	2	—	15
29.5-32.8	—	—	—	4	5	—	—	9
>32.8	—	—	—	1	12	—	—	13
Total	**7**	**76**	**278**	**297**	**60**	**2**	**—**	**720**

Table 3
Estimated Magnitude of Shallow-Water Waves (Sea and Swell) Approaching St. Paul Harbor from the Directions Indicated

Wave Height, ft	Occurrences per Wave Period, sec[1]							
	4.4-6.0	6.1-8.0	8.1-10.5	10.6-13.3	13.4-15.3	15.4-18.1	>18.2	Total
West-northwest								
0-4	21	41	109	1	—	—	—	172
4-7	7	59	137	114	1	—	—	318
7-10	—	—	61	92	6	—	—	159
10-13	—	—	9	3	15	—	—	27
13-16	—	—	—	—	4	1	—	5
16-19	—	—	—	—	—	1	—	1
19-22	—	—	—	—	—	1	—	1
>22	—	—	—	—	—	1	—	1
Total	**28**	**100**	**316**	**210**	**26**	**4**	—	**684**
West								
0-4	2	5	10	—	—	—	—	17
4-7	19	64	124	3	—	—	—	210
7-10	18	65	220	46	—	—	—	349
10-13	1	51	152	142	3	—	—	349
13-16	—	—	29	161	12	—	—	202
16-19	—	—	2	82	16	1	—	101
19-22	—	—	—	13	14	—	—	27
22-25	—	—	—	5	8	—	—	13
25-28	—	—	—	1	4	1	—	6
28-31	—	—	—	1	3	1	—	5
>31	—	—	—	—	2	—	—	2
Total	**40**	**185**	**537**	**454**	**62**	**3**	—	**1,281**
West-southwest								
0-4	1	2	4	—	—	—	—	7
4-7	9	50	65	3	—	—	—	127
7-10	16	81	159	31	1	—	—	288
10-13	—	48	76	87	—	—	—	211
13-16	—	3	55	134	4	—	—	196
16-19	—	—	24	64	23	1	—	112
19-22	—	—	4	35	20	—	—	59
22-25	—	—	1	17	10	2	—	30
25-28	—	—	—	9	5	—	—	14
>28	—	—	—	1	—	2	—	3
Total	**26**	**184**	**388**	**381**	**63**	**5**	—	**1,047**

(Continued)

[1] Occurrences compiled for period 1966-1975. Each occurrence represents a 6-hr duration.

Table 3 (Concluded)

Wave Height, ft	Occurrences per Wave Period, sec[1]							
	4.4-6.0	6.1-8.0	8.1-10.5	10.6-13.3	13.4-15.3	15.4-18.1	>18.2	Total
Southwest								
0-4	1	4	52	—	—	—	—	57
4-7	7	76	121	23	—	—	—	227
7-10	10	24	116	174	3	—	—	327
10-13	—	1	19	70	17	—	—	107
13-16	—	—	6	75	36	1	—	118
16-19	—	—	—	21	9	2	—	32
>19	—	—	—	—	3	1	—	4
Total	**18**	**105**	**314**	**363**	**68**	**4**	—	**872**
South-southwest								
0-4	5	3	—	12	—	—	—	20
4-7	2	58	164	167	—	—	—	391
7-10	—	13	52	88	4	—	—	157
10-13	—	2	25	25	24	—	—	76
13-16	—	—	36	5	15	2	—	58
16-19	—	—	1	—	5	—	—	6
>19	—	—	—	—	12	—	—	12
Total	**7**	**76**	**278**	**297**	**60**	**2**	—	**720**

Table 4
Wave Heights for Existing Conditions for Test Waves from West

Test Wave		Wave Height, ft, at Indicated Gauge Location																
Period, sec	Height, ft	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16	Gauge 17
swl = +5.0 ft																		
12.0	16.0	8.7	4.4	4.1	2.7	2.7	2.9	2.7	2.9	1.7	2.1	1.7	—	—	18.5	15.0	—	15.3
	19.0	9.4	5.0	4.5	3.1	2.9	3.3	3.0	3.0	1.9	2.4	1.8	—	—	19.3	16.1	—	15.1
14.0	16.0	9.1	5.1	4.8	3.1	3.1	3.3	3.0	3.2	2.0	2.3	1.8	—	—	19.2	14.2	—	12.5
16.0	19.0	10.0	5.6	5.2	3.5	3.3	3.6	3.4	3.6	1.9	2.7	2.0	—	—	19.6	14.2	—	11.8
swl = +7.0 ft																		
6.0	7.0	4.0	2.3	1.7	1.0	0.9	1.1	1.5	1.0	0.8	0.8	0.5	—	—	7.0	6.7	—	6.9
	10.0	5.2	2.7	2.0	1.4	1.3	1.4	1.8	1.3	1.0	1.0	0.7	—	—	9.1	8.1	—	8.3
8.0	10.0	5.3	3.3	2.4	1.5	1.2	1.5	2.4	1.7	1.2	1.6	1.0	—	—	10.2	9.9	—	10.8
10.0	10.0	6.4	4.2	2.5	1.8	1.5	1.9	2.6	2.2	1.3	1.9	1.2	—	—	12.5	10.8	—	12.7
	19.0	9.6	5.8	4.3	3.3	3.1	3.8	3.2	3.3	1.8	2.6	1.8	—	—	20.3	19.2	—	19.6
12.0	16.0	9.7	6.4	5.0	3.4	3.0	3.7	3.3	3.3	1.9	2.7	1.9	—	—	20.3	16.5	—	15.6
	19.0	10.4	6.6	5.0	3.5	3.2	4.3	3.6	3.6	2.1	2.9	1.9	—	—	21.2	[illegible]	—	16.4
14.0	16.0	9.9	6.4	5.2	3.4	3.4	4.0	3.6	3.7	2.1	2.8	1.9	—	—	20.3	15.3	—	13.0

(Continued)

Table 4 (Concluded)

Test Wave		Wave Height, ft, at Indicated Gauge Location																
Period, sec	Height, ft	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16	Gauge 17
swl = +7.0 ft (continued)																		
16.0	14.4	11.0	6.8	5.4	3.4	3.1	3.8	4.0	3.4	2.2	3.3	2.1	1.8	13.2	19.9	14.5	12.5	12.6
	15.3	11.5	7.0	5.5	3.4	3.2	3.9	4.1	3.4	2.4	3.5	2.4	—	—	20.2	15.1	—	13.0
	16.2	12.1	7.0	5.3	3.5	3.1	3.9	4.1	3.5	2.5	3.5	2.4	—	—	20.3	15.3	—	13.2
	17.0	12.5	7.2	5.4	3.5	3.3	3.9	4.2	3.6	2.4	3.6	2.5	—	—	20.9	16.1	—	13.4
	19.0	13.3	7.4	5.5	3.7	3.4	4.0	4.3	3.6	2.7	3.3	2.2	2.0	16.0	21.3	17.1	13.3	13.3
20.0	14.0	12.9	7.9	5.7	3.8	3.4	4.3	4.8	4.6	2.6	3.9	2.5	2.0	16.4	21.3	15.6	13.7	14.4

Table 5
Wave Heights for Plans 2-4 for Representative Test Waves from West with the +7.0-ft swl

Test Wave		Wave Height, ft, at Indicated Gauge Location																
Period, sec	Height, ft	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16	Gauge 17
Plan 2																		
16.0	14.4	11.1	6.5	5.3	3.4	3.0	3.6	3.9	3.3	2.2	3.1	2.1	1.7	14.0	19.1	12.5	9.6	11.1
	19.0	12.6	6.9	5.1	3.5	3.2	4.0	4.3	3.6	2.5	3.3	2.2	1.9	15.0	20.5	13.7	11.0	11.8
20.0	14.0	12.1	7.5	5.4	3.7	3.3	4.1	4.5	3.8	2.5	3.6	2.4	1.8	14.4	21.0	13.6	10.9	12.5
Plan 3																		
16.0	14.4	9.9	6.1	5.0	3.3	3.0	3.5	3.5	3.1	2.1	2.9	2.0	1.6	11.9	18.8	11.5	9.9	11.3
	19.0	11.4	6.5	5.2	3.6	3.4	4.3	3.8	3.4	2.4	3.0	2.1	1.8	14.0	20.5	12.5	11.3	11.8
20.0	14.0	10.4	6.7	5.3	3.6	3.2	3.9	4.0	3.6	2.4	3.3	2.2	1.7	13.3	20.5	12.2	11.0	12.6
Plan 4																		
16.0	14.4	10.1	6.1	5.2	3.3	2.9	3.6	3.7	3.2	2.1	2.9	2.0	1.6	11.9	19.3	11.4	10.4	11.6
	19.0	11.9	6.7	5.3	3.7	3.4	4.3	3.9	3.5	2.4	3.1	2.2	1.9	14.4	20.8	12.6	11.2	12.0
20.0	14.0	11.0	6.9	5.4	3.7	3.2	4.2	4.1	3.7	2.4	3.4	2.2	1.9	14.3	21.0	12.3	11.1	12.8

Table 6
Wave Heights for Plans 5-9 for Representative Test Waves from West with the +7.0-ft swl

Test Wave		Wave Height, ft, at Indicated Gauge Location																
Period, sec	Height, ft	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16	Gauge 17
Plan 5																		
16.0	14.4	8.5	4.9	5.1	2.9	2.6	3.1	2.9	2.3	2.6	2.1	1.8	1.8	12.0	18.9	12.1	11.1	11.9
	19.0	10.2	5.4	5.1	3.2	3.0	3.8	3.3	2.6	2.8	2.3	2.1	2.1	14.8	20.6	13.4	12.0	12.5
20.0	14.0	9.6	5.5	5.2	3.2	2.9	3.4	3.2	2.5	2.9	2.4	2.2	2.0	15.0	20.4	13.1	12.0	13.0
Plan 6																		
16.0	14.4	8.7	5.0	5.1	2.7	2.5	2.6	2.9	2.0	2.1	2.0	—	1.4	12.3	19.5	12.5	11.4	12.3
	19.0	10.5	5.1	4.9	2.9	2.9	3.1	3.0	2.1	2.1	2.1	—	1.6	14.8	20.7	12.9	11.4	12.5
20.0	14.0	9.4	5.1	5.1	2.8	2.8	2.8	3.0	2.1	2.2	2.1	—	1.6	14.9	20.4	13.1	11.7	13.0
Plan 7																		
16.0	19.0	10.4	5.2	4.9	2.9	2.8	3.0	3.1	2.2	2.2	2.1	—	1.8	14.8	20.5	13.1	11.6	12.4
20.0	14.0	9.4	5.2	5.4	3.1	3.1	2.9	3.1	2.2	2.2	2.1	—	1.8	14.6	20.0	12.8	11.5	13.1
Plan 8																		
16.0	19.0	10.4	5.1	5.1	2.9	3.1	3.1	3.1	2.2	2.2	2.1	—	1.7	14.9	20.4	13.1	11.5	12.5
20.0	14.0	9.0	4.8	5.2	3.0	2.9	2.7	2.9	2.0	2.0	2.0	—	1.6	13.9	20.7	12.8	11.8	13.3
Plan 9																		
16.0	19.0	10.3	5.1	5.0	3.0	3.0	3.0	3.1	2.2	2.2	2.0	—	1.7	14.9	20.5	13.1	11.8	12.5
20.0	14.0	9.5	4.9	5.1	2.9	2.9	2.6	2.9	2.0	2.0	2.0	—	1.5	14.1	20.5	12.9	11.9	12.9

Table 7
Wave Heights for Plan 10 for Test Waves from West

Test Wave		Wave Height, ft, at Indicated Gauge Location																
Period, sec	Height, ft	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16	Gauge 17
swl = +5.0 ft																		
12.0	16.0	8.1	4.4	3.8	2.5	2.4	2.5	2.4	2.0	2.3	1.8	1.6	1.8	11.7	18.9	12.9	11.4	11.1
	19.0	8.6	4.9	3.9	2.8	2.6	3.0	2.7	2.4	2.6	1.9	1.7	2.0	12.7	20.1	13.2	11.9	13.7
14.0	16.0	8.2	4.5	4.3	2.7	2.5	2.8	2.4	2.2	2.6	1.8	1.6	1.9	10.9	19.2	11.9	11.2	11.2
16.0	19.0	9.2	4.9	4.5	2.9	3.1	3.1	2.7	2.4	2.5	2.1	1.8	2.1	13.4	20.0	12.2	10.8	12.0
swl = +7.0 ft																		
6.0	7.0	3.1	1.8	1.7	1.1	1.0	1.0	0.9	0.8	0.7	0.6	0.4	0.3	5.9	6.8	6.0	5.2	5.1
	10.0	3.8	2.5	2.1	1.3	1.1	1.2	1.2	1.0	1.0	0.8	0.5	0.4	7.1	8.8	7.4	5.9	8.0
8.0	10.0	4.2	3.0	2.2	1.4	1.0	1.3	1.6	1.1	1.2	1.0	0.7	0.8	7.2	10.4	7.4	8.3	11.1
10.0	10.0	5.1	3.5	2.4	1.5	1.1	1.6	1.9	1.5	1.5	1.3	1.1	1.0	7.3	12.8	9.1	10.8	10.3
	19.0	8.8	4.9	3.9	2.9	2.5	3.3	2.7	2.3	2.3	2.0	1.6	1.6	13.7	20.0	14.0	12.8	16.4
12.0	16.0	8.5	5.2	4.2	2.8	2.7	3.2	2.8	2.4	2.6	2.1	1.7	1.7	12.0	19.7	13.9	12.5	13.8
	19.0	9.0	5.4	4.4	3.0	2.9	3.6	3.1	2.5	2.8	2.2	1.7	2.1	12.9	21.0	14.1	12.9	15.1
14.0	16.0	8.2	4.8	4.6	2.8	2.5	3.1	2.7	2.2	2.6	2.0	1.7	1.9	10.7	19.7	12.8	11.8	11.2
16.0	14.4	8.4	4.9	5.0	2.9	2.7	3.2	2.8	2.3	2.7	2.1	1.8	1.9	11.8	19.0	12.0	11.1	11.3
	15.3	8.3	4.8	5.0	2.8	2.8	3.1	2.7	2.2	2.8	2.1	1.8	2.0	11.7	19.4	12.2	11.4	11.2
	16.2	8.7	5.0	5.1	3.1	2.9	3.2	3.0	2.5	2.9	2.2	1.9	2.1	12.4	19.6	12.5	11.2	11.3
	17.0	9.8	5.6	5.3	3.3	3.3	3.5	3.2	2.6	3.0	2.3	2.1	2.2	14.9	20.2	12.5	11.5	12.1
	19.0	10.0	5.7	5.1	3.3	3.3	3.6	3.2	2.7	3.0	2.4	2.1	2.3	15.2	20.7	13.2	11.5	12.2
20.0	14.0	9.4	5.9	5.4	3.3	3.2	3.6	3.3	2.7	3.2	2.6	2.2	2.2	15.0	20.9	12.3	11.9	12.9

Table 8
Wave Heights for Plan 11 for Test Waves from West

Test Wave		Wave Height, ft, at Indicated Gauge Location																
Period, sec	Height, ft	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16	Gauge 17
swl = +5.0 ft																		
12.0	16.0	8.0	4.4	3.7	2.5	2.3	2.6	2.2	1.6	1.7	1.6	—	1.5	11.7	19.5	13.1	11.8	11.3
	19.0	8.8	5.0	4.2	2.6	2.4	2.7	2.6	1.9	2.0	1.8	—	1.6	13.0	20.6	13.2	11.5	13.9
14.0	16.0	7.9	4.4	4.2	2.5	2.3	2.5	2.4	1.7	1.8	1.6	—	1.7	10.9	20.2	11.9	11.0	11.4
16.0	19.0	9.3	4.8	4.4	2.8	2.8	2.9	2.6	2.0	1.9	1.8	—	1.8	13.6	20.0	11.7	11.0	12.4
swl = +7.0 ft																		
6.0	7.0	3.1	2.0	1.7	1.1	1.0	1.0	1.0	0.8	0.8	0.6	—	0.3	5.8	6.8	6.4	4.8	6.4
	10.0	4.0	2.7	2.1	1.3	1.1	1.2	1.3	1.1	1.1	0.8	—	0.4	7.3	9.2	7.4	6.0	8.1
8.0	10.0	4.4	3.0	2.2	1.4	1.0	1.3	1.7	1.1	1.1	1.0	—	0.7	7.3	10.9	7.6	8.4	11.2
10.0	10.0	5.4	3.6	2.5	1.5	1.1	1.4	1.8	1.5	1.2	1.4	—	0.9	7.7	12.6	9.5	10.8	10.0
	19.0	8.9	4.8	3.6	2.6	2.4	2.9	2.6	1.8	1.8	1.7	—	1.3	13.3	20.2	14.1	12.9	16.4
12.0	16.0	8.3	4.7	4.2	2.6	2.4	2.7	2.5	1.8	1.9	1.8	—	1.4	11.8	19.9	14.1	12.6	12.1
	19.0	9.2	5.3	4.4	2.9	2.7	3.0	2.9	2.0	2.0	1.9	—	1.6	13.1	21.3	14.3	12.6	14.7
14.0	16.0	8.6	4.8	4.6	2.9	2.6	2.8	2.5	1.9	1.9	1.9	—	1.5	11.3	20.2	12.6	11.8	11.3
16.0	14.4	8.1	4.7	4.8	2.9	2.5	2.7	2.7	2.0	2.0	2.1	—	1.7	11.4	19.0	12.1	11.2	11.2
	15.3	8.4	4.9	4.8	2.9	2.7	2.8	2.7	2.0	2.0	2.1	—	1.7	11.5	19.6	12.5	11.4	11.2
	16.2	8.8	5.0	5.0	3.1	2.8	2.8	2.9	2.1	2.0	2.1	—	1.7	12.9	19.9	12.5	11.2	11.7
	17.0	9.9	5.4	5.3	3.2	2.9	3.3	3.1	2.3	2.1	2.3	—	1.7	15.1	20.2	12.8	11.4	12.3
	19.0	9.9	5.4	5.1	3.3	3.2	3.3	3.1	2.3	2.1	2.2	—	1.7	14.3	20.9	13.2	11.5	12.5
20.0	14.0	9.0	5.4	5.2	3.2	3.0	3.1	3.1	2.3	2.3	2.4	—	1.7	14.9	20.7	13.0	11.5	13.0

Table 9
Wave Heights for Plan 11 for Test Waves from West-Northwest

Test Wave		Wave Height, ft, at Indicated Gauge Location																
Period, sec	Height, ft	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16	Gauge 17
swl = +5.0 ft																		
12.0	16.0	8.2	4.6	3.7	2.2	2.0	2.4	2.4	1.7	1.8	1.6	—	1.5	11.3	18.4	12.0	10.8	15.8
	19.0	9.6	5.5	4.2	2.5	2.4	3.2	2.9	2.1	2.3	2.0	—	1.8	13.5	19.3	12.6	11.7	15.5
14.0	16.0	9.5	5.0	4.2	2.8	2.6	2.9	2.6	2.0	2.1	1.9	—	1.8	13.3	19.4	11.5	10.9	13.9
16.0	19.0	10.8	5.4	4.4	2.8	2.8	3.0	3.0	2.2	2.2	2.1	—	2.0	15.6	20.2	12.4	11.0	12.9
swl = +7.0 ft																		
6.0	7.0	3.8	1.9	1.6	0.9	0.9	0.8	1.0	0.8	0.7	0.7	—	0.4	6.8	7.0	5.8	5.1	6.1
	10.0	4.7	2.6	2.0	1.2	0.9	1.1	1.4	1.1	0.9	0.9	—	0.5	8.7	9.3	7.2	6.4	7.8
8.0	10.0	4.9	2.9	2.2	1.3	1.0	1.3	1.7	1.2	1.2	1.1	—	0.7	8.0	10.7	7.2	8.1	10.9
10.0	10.0	5.2	3.4	2.5	1.6	1.1	1.7	1.7	1.5	1.2	1.3	—	1.0	8.4	11.9	9.0	8.7	12.3
	19.0	9.8	5.4	4.0	2.9	2.9	3.2	2.8	2.1	2.2	1.8	—	1.5	13.5	18.8	13.5	12.7	19.1
12.0	16.0	9.0	5.1	4.2	2.8	2.4	2.9	2.6	2.0	2.0	1.9	—	1.5	12.2	17.9	13.0	11.4	16.0
	19.0	10.0	5.6	4.7	3.2	2.9	3.5	3.1	2.2	2.3	2.1	—	1.6	13.6	19.9	13.8	12.6	16.1
14.0	16.0	10.3	5.7	4.8	3.1	2.8	3.4	2.9	2.2	2.2	2.0	—	1.8	13.1	20.3	12.3	11.8	14.3
16.0	14.4	8.6	5.1	4.7	3.0	2.9	2.8	2.8	2.1	2.1	2.1	—	1.7	12.3	20.1	11.3	11.6	12.6
	15.3	8.6	5.1	4.8	3.1	2.9	3.0	2.9	2.1	2.2	2.1	—	1.7	12.2	20.4	11.7	11.4	14.4
	16.2	9.1	5.2	4.9	3.0	3.0	3.1	2.9	2.1	2.2	2.2	—	1.8	12.8	20.7	12.2	11.7	14.4
	17.0	10.4	5.5	5.0	3.1	3.0	3.2	3.0	2.2	2.3	2.3	—	1.8	14.0	20.9	12.8	12.1	13.7
	19.0	11.3	5.8	4.8	3.2	3.3	3.4	3.1	2.4	2.3	2.4	—	1.8	15.1	21.5	13.1	12.2	13.9
20.0	14.0	10.1	5.5	5.0	3.2	3.4	3.2	3.1	2.3	2.3	2.2	—	1.9	13.1	21.8	13.8	11.8	13.1

Table 10
Wave Heights for Plan 12 for Representative Test Waves from West with the +7.0-ft swl

Test Wave		Wave Height, ft, at Indicated Gauge Location																
Period, sec	Height, ft	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6	Gauge 7	Gauge 8	Gauge 9	Gauge 10	Gauge 11	Gauge 12	Gauge 13	Gauge 14	Gauge 15	Gauge 16	Gauge 17
8.0	10.0	4.3	3.0	2.0	1.4	0.9	1.2	1.6	1.1	1.1	1.0	—	0.7	7.3	10.3	7.4	8.4	9.7
12.0	19.0	8.6	5.5	4.4	3.1	2.8	3.0	2.9	2.2	1.9	1.9	—	1.5	14.7	20.4	13.8	12.9	13.6
14.0	16.0	8.6	5.0	4.7	2.7	2.5	2.8	2.7	2.1	1.9	2.0	—	1.5	12.1	19.3	12.6	11.6	11.3
16.0	14.4	8.4	5.2	5.0	3.1	2.7	3.0	2.9	2.1	2.1	2.2	—	1.8	12.8	19.0	11.8	10.8	11.6
	19.0	9.7	5.6	5.1	3.2	3.2	3.5	3.2	2.2	2.0	2.3	—	1.7	15.4	20.5	13.4	11.8	12.7
20.0	14.0	9.2	5.4	5.0	3.1	3.2	3.1	3.0	2.2	2.1	2.3	—	1.6	15.9	20.7	12.7	11.7	12.9

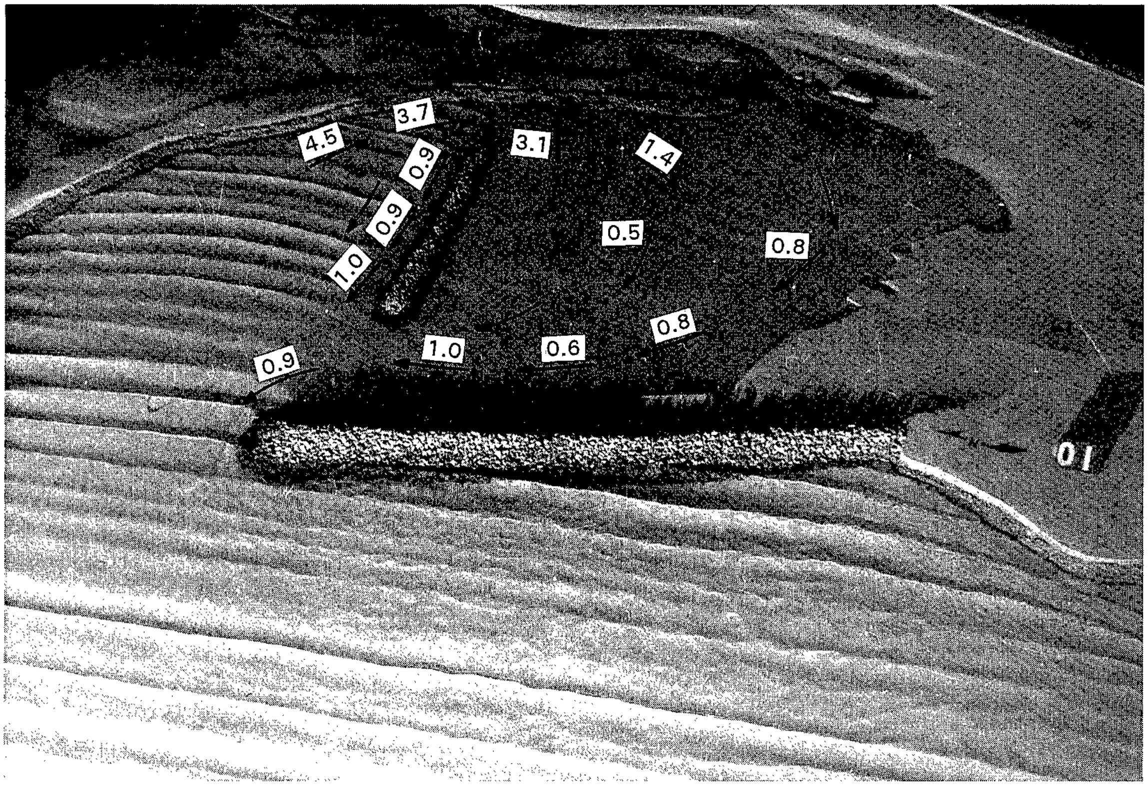


Photo 1. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 6-sec, 7-ft test waves from west; swl = +3.2 ft

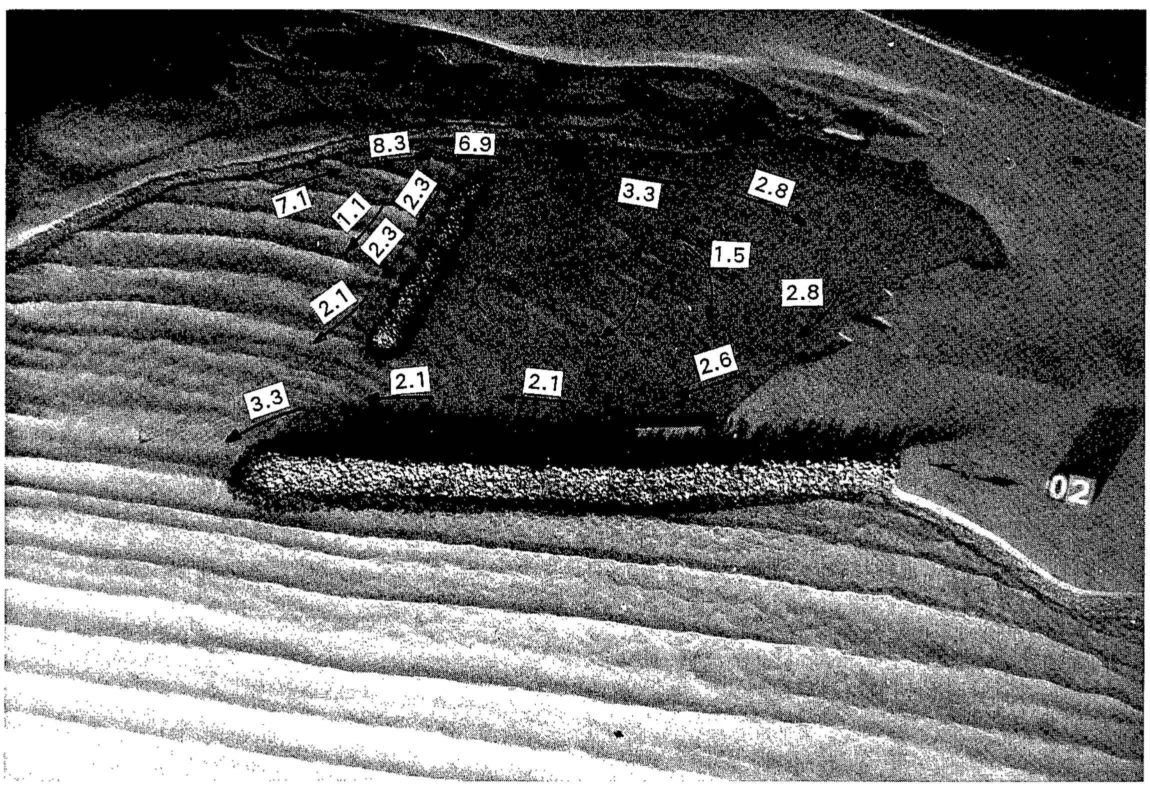


Photo 2. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 8-sec, 10-ft test waves from west; swl = +3.2 ft

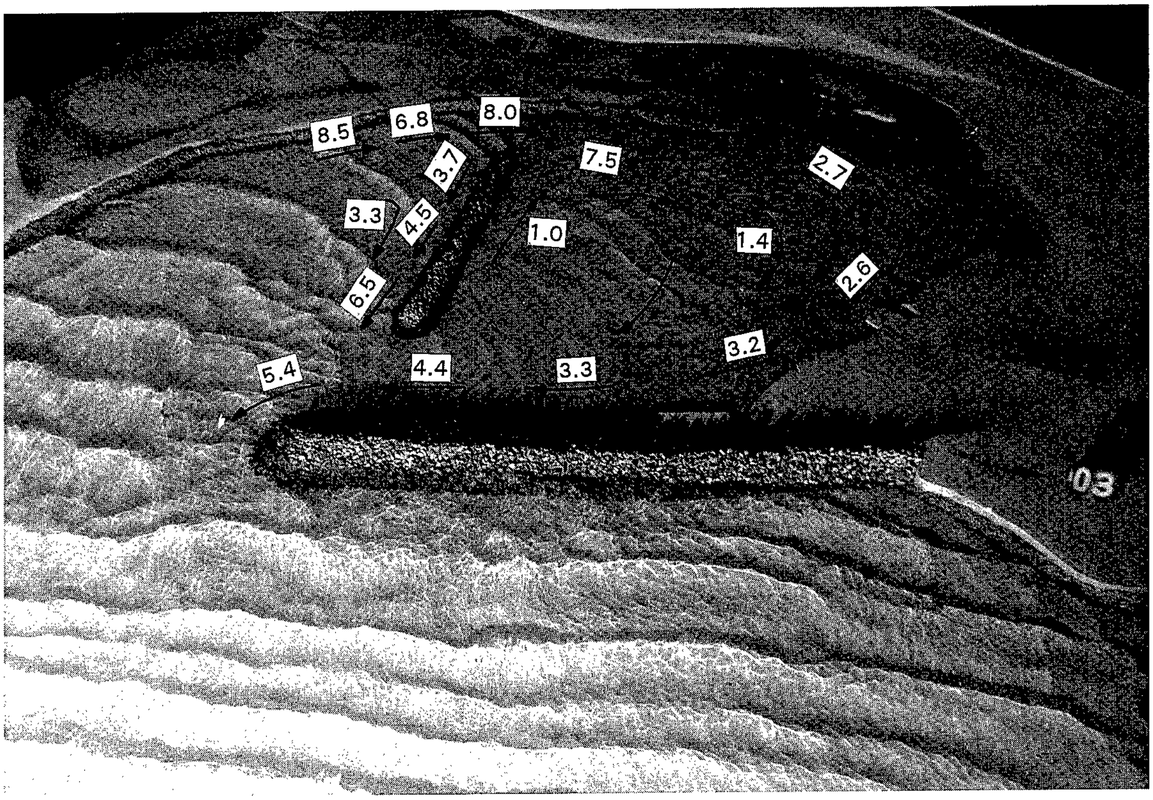


Photo 3. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 10-sec, 19-ft test waves from west; swl = +3.2 ft

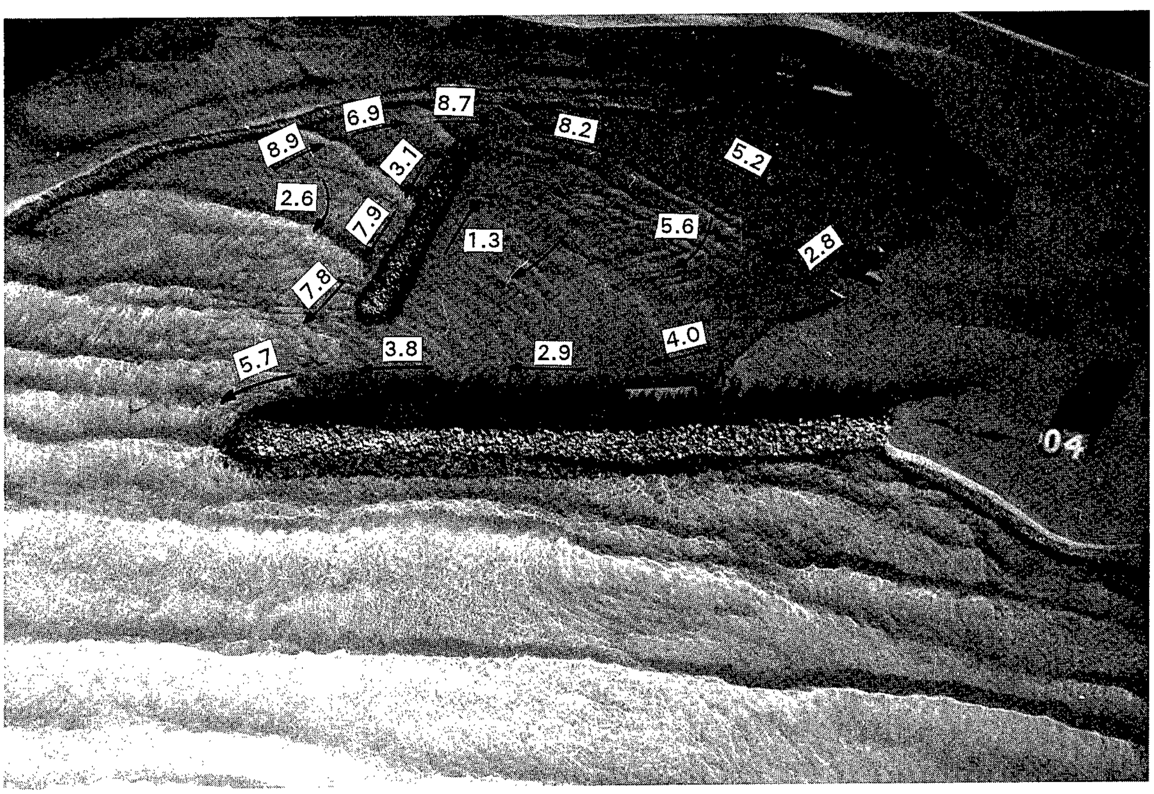


Photo 4. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 12-sec, 16-ft test waves from west; swl = +3.2 ft

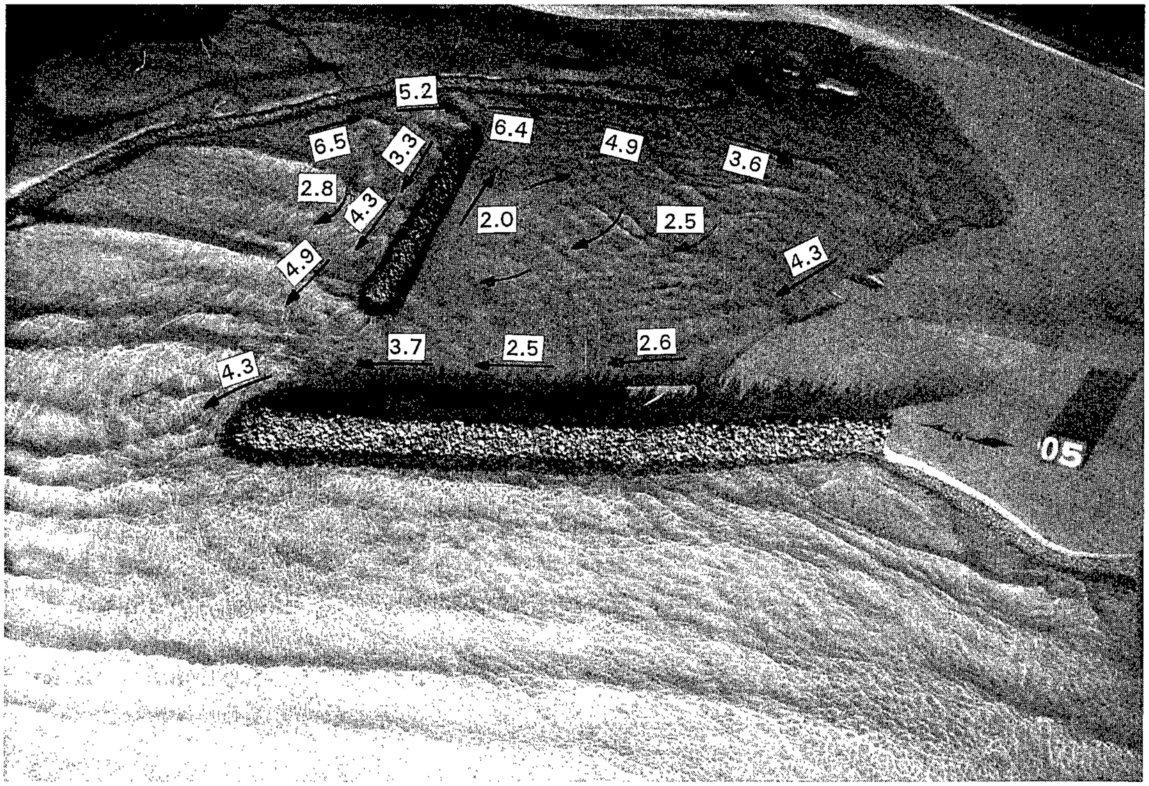


Photo 5. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 16-sec, 19-ft test waves from west; swl = +3.2 ft

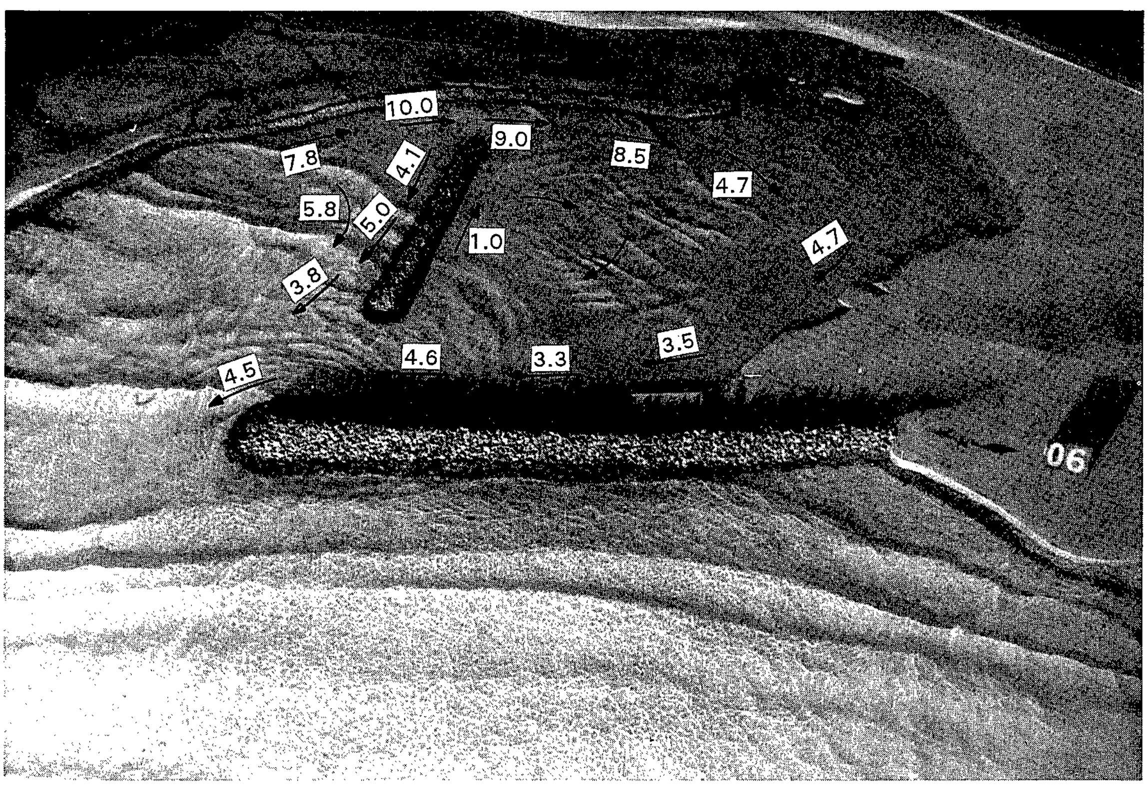


Photo 6. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for existing conditions; 20-sec, 14-ft test waves from west; swl = +3.2 ft

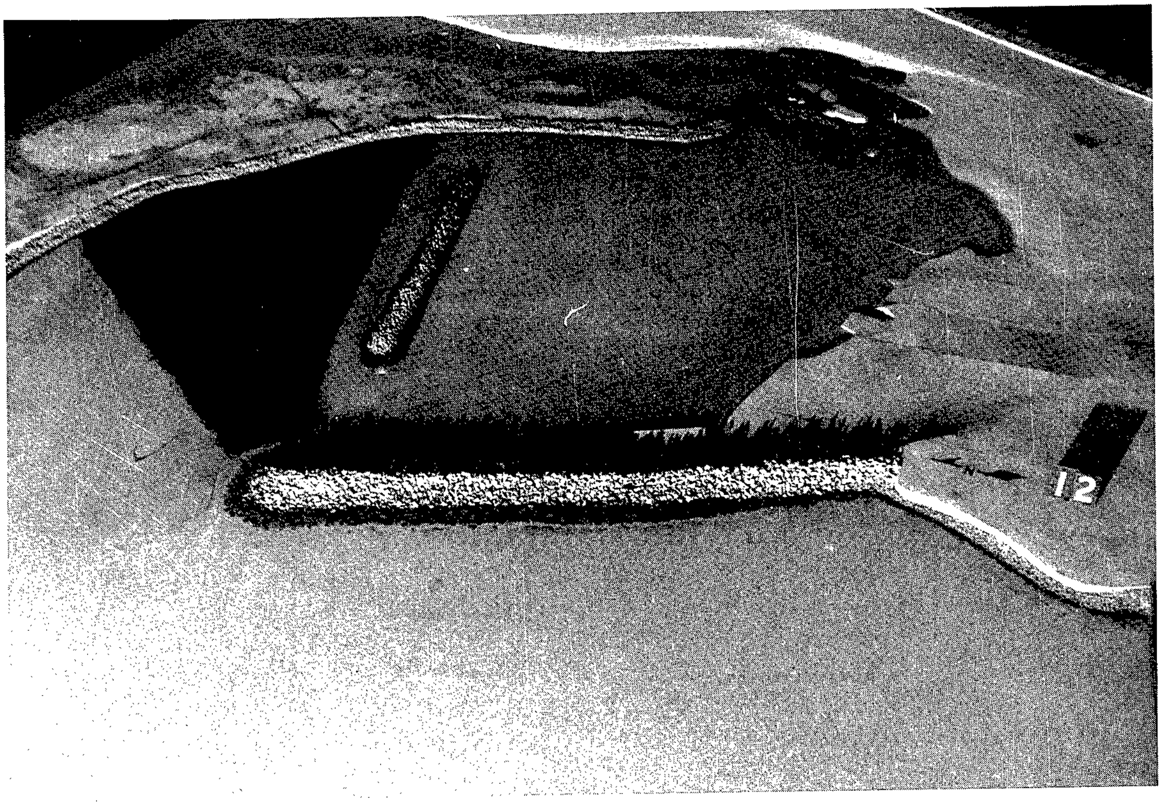


Photo 7. Placement of tracer material for existing conditions prior to model testing

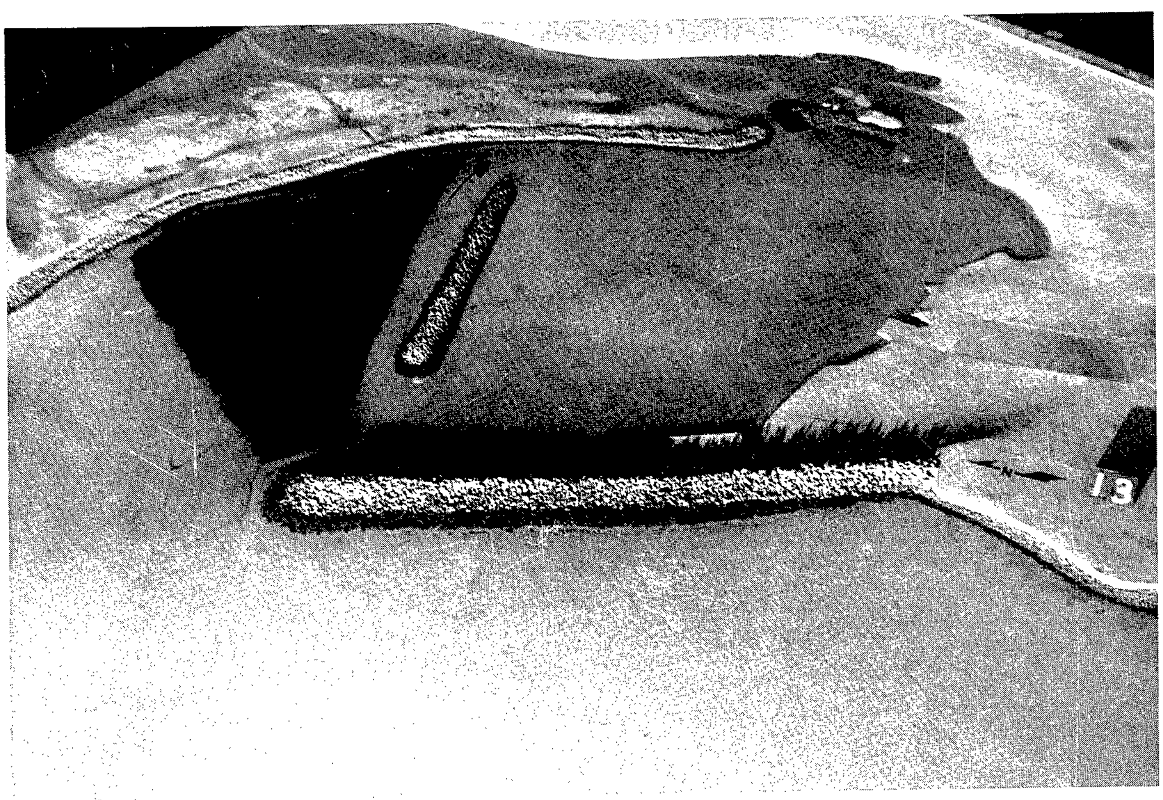


Photo 8. General movement of tracer material and subsequent deposits for existing conditions; 8-sec, 10-ft test waves from west; swl = +3.2 ft (test 1 of a series)

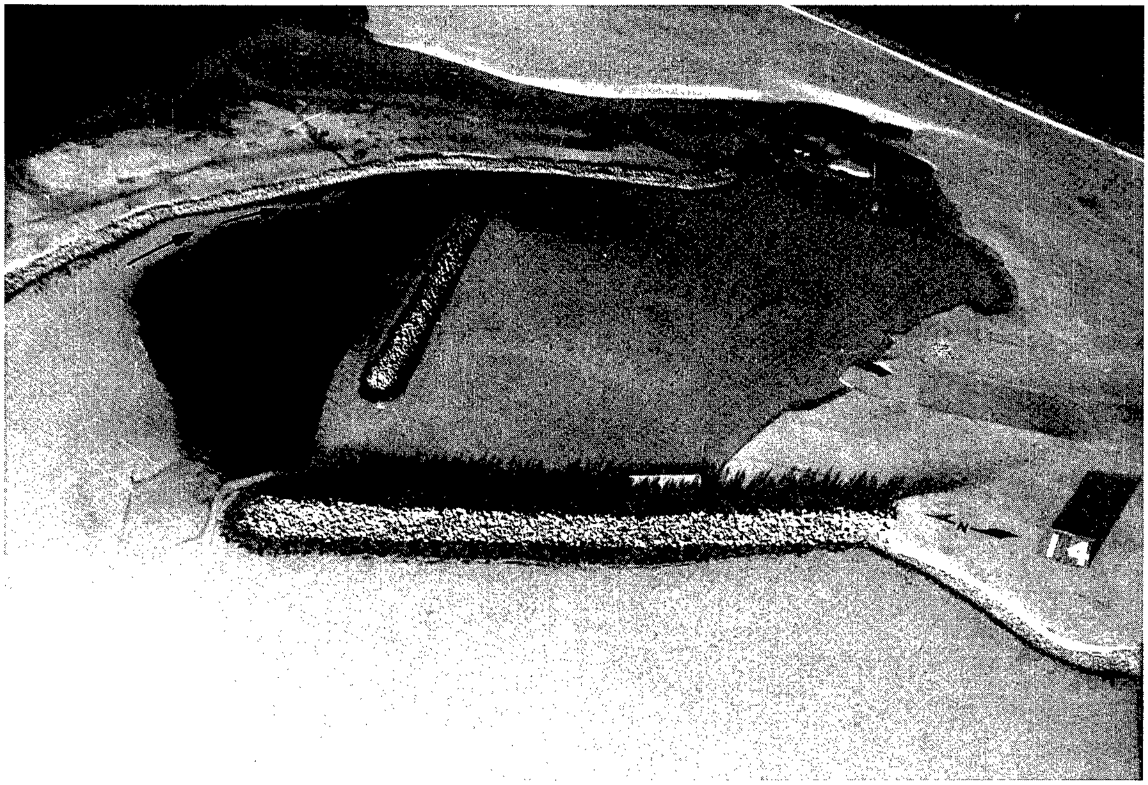


Photo 9. General movement of tracer material and subsequent deposits for existing conditions; 10-sec, 19-ft test waves from west; swl = +3.2 ft (test 2 of a series)

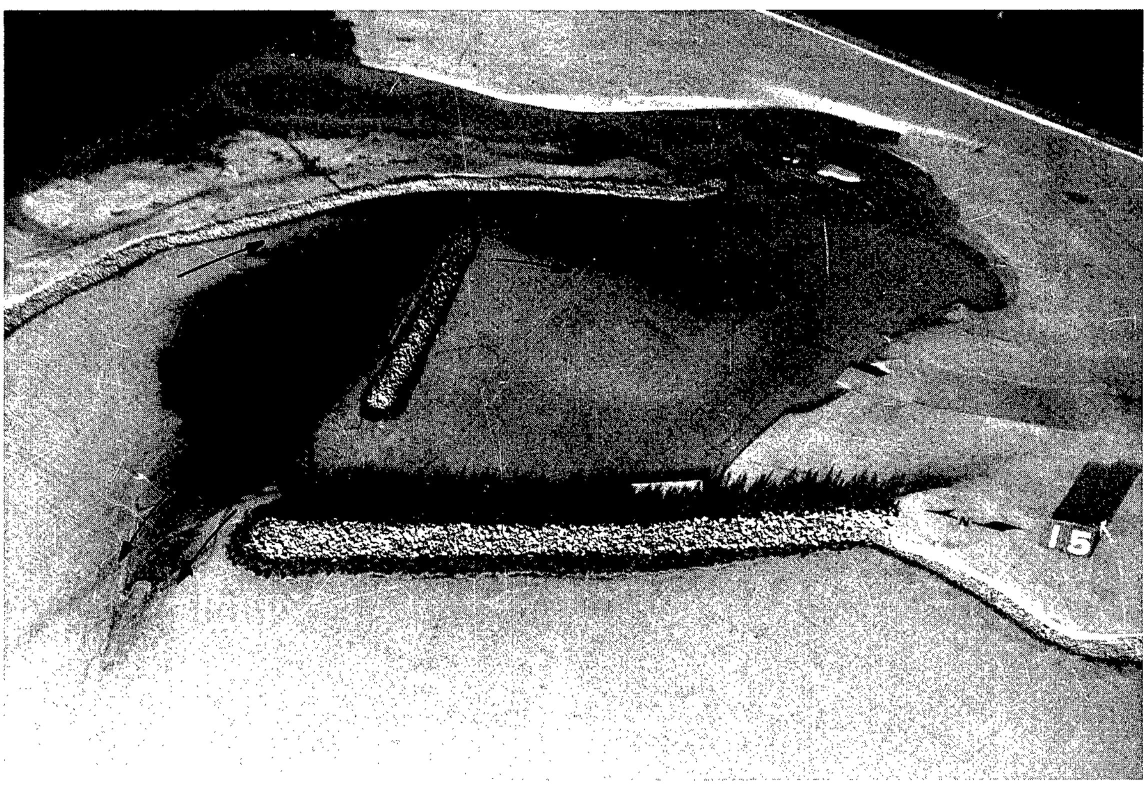


Photo 10. General movement of tracer material and subsequent deposits for existing conditions; 12-sec, 16-ft test waves from west; swl = +3.2 ft (test 3 of a series)

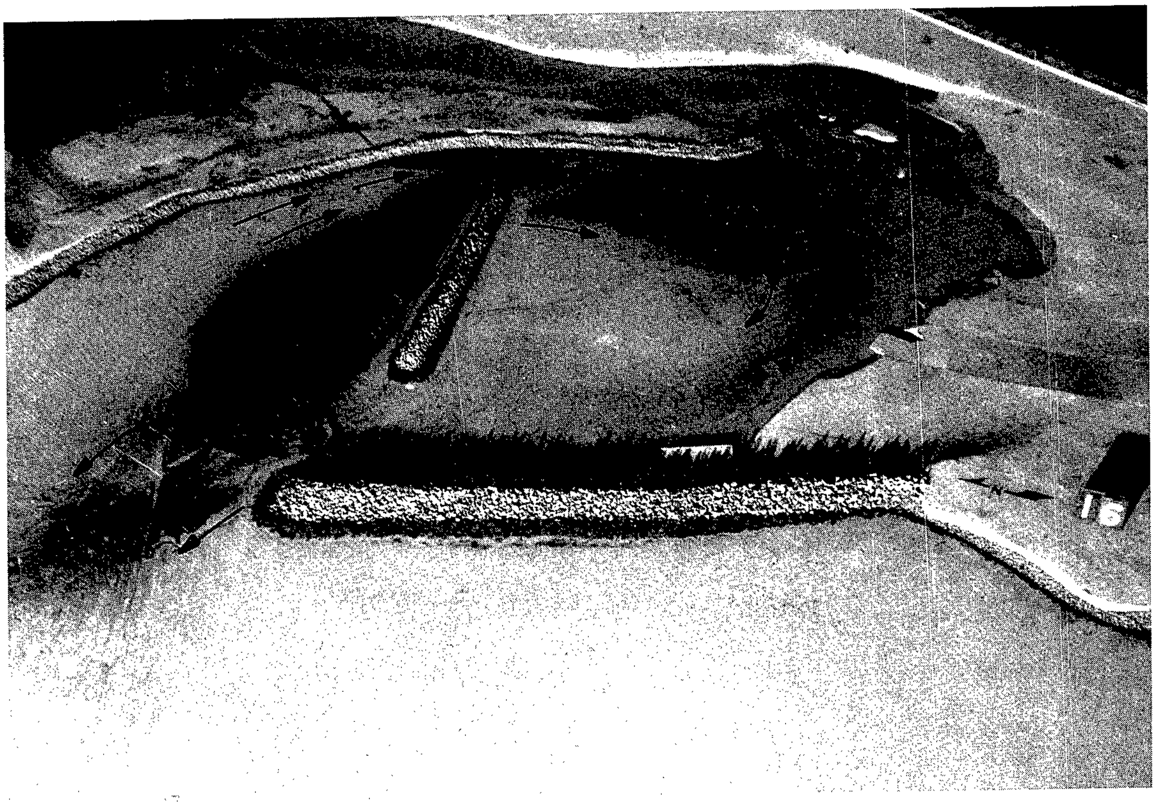


Photo 11. General movement of tracer material and subsequent deposits for existing conditions; 16-sec, 19-ft test waves from west; swl = +3.2 ft (test 4 of a series)

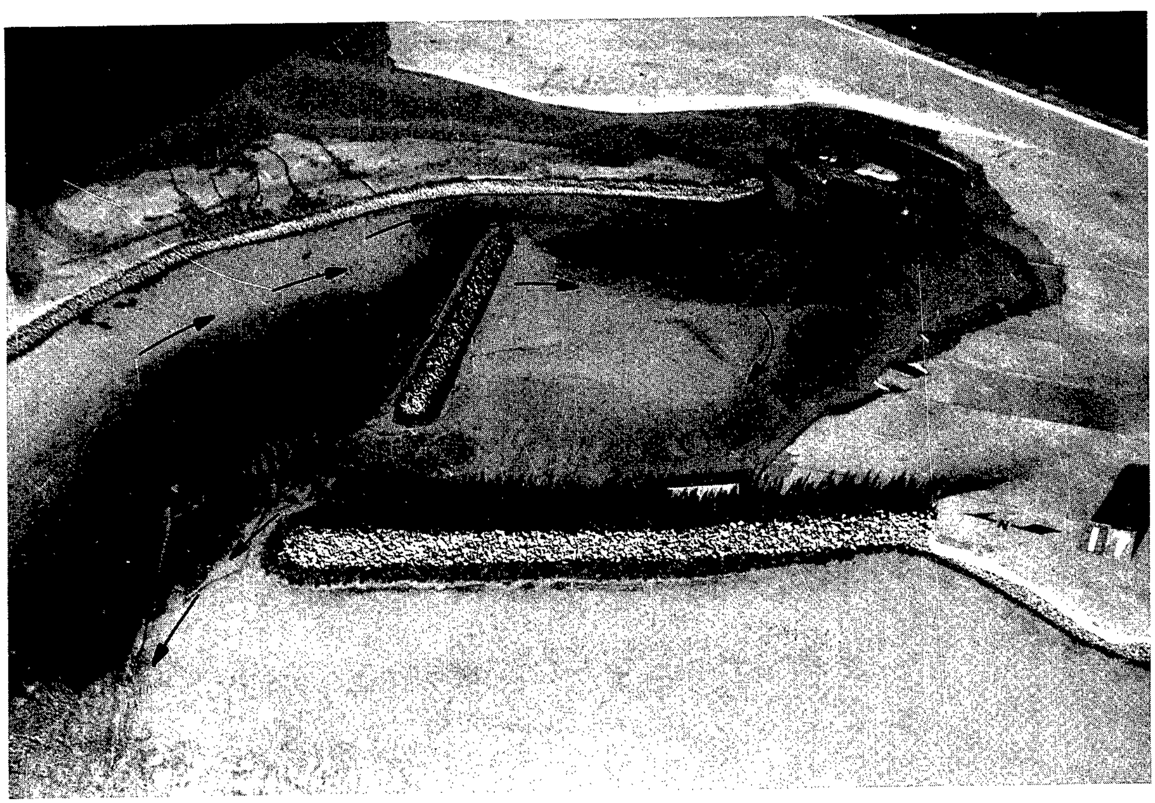


Photo 12. General movement of tracer material and subsequent deposits for existing conditions; 20-sec, 14-ft test waves from west; swl = +3.2 ft (test 5 of a series)

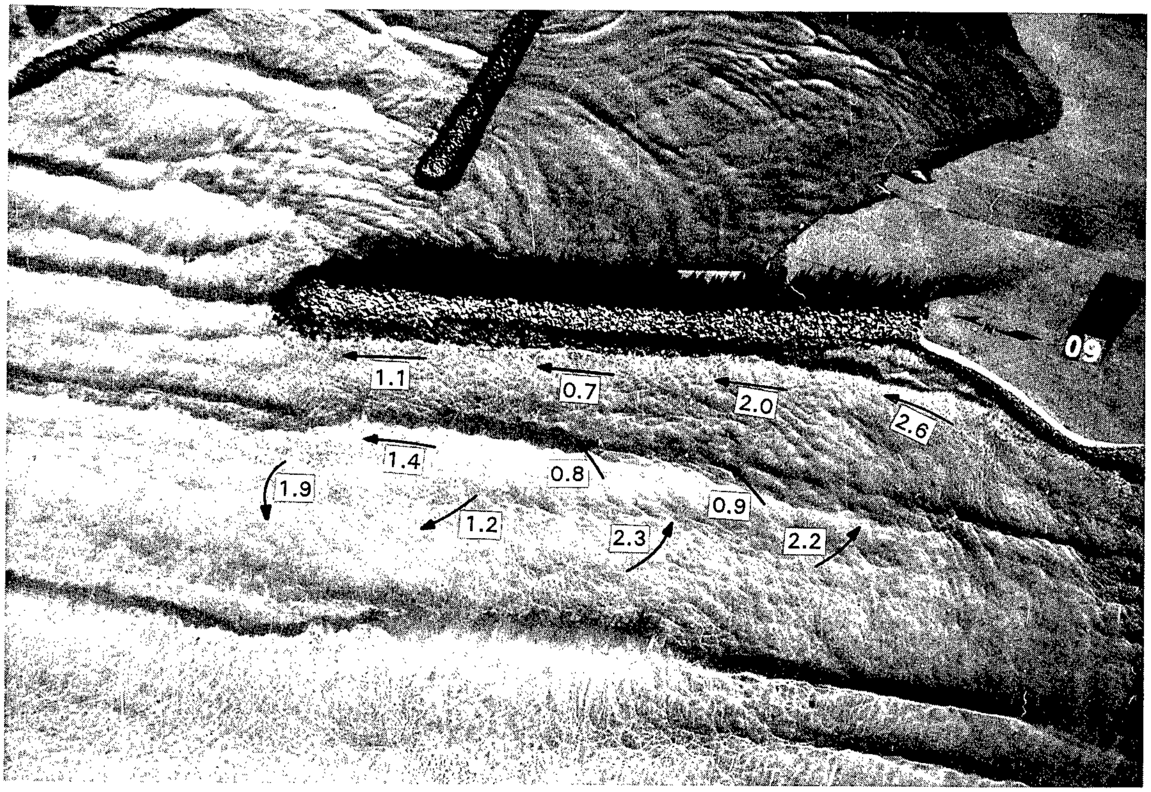


Photo 13. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for existing conditions; 16-sec, 14.4-ft test waves from west; swl = +7.0 ft

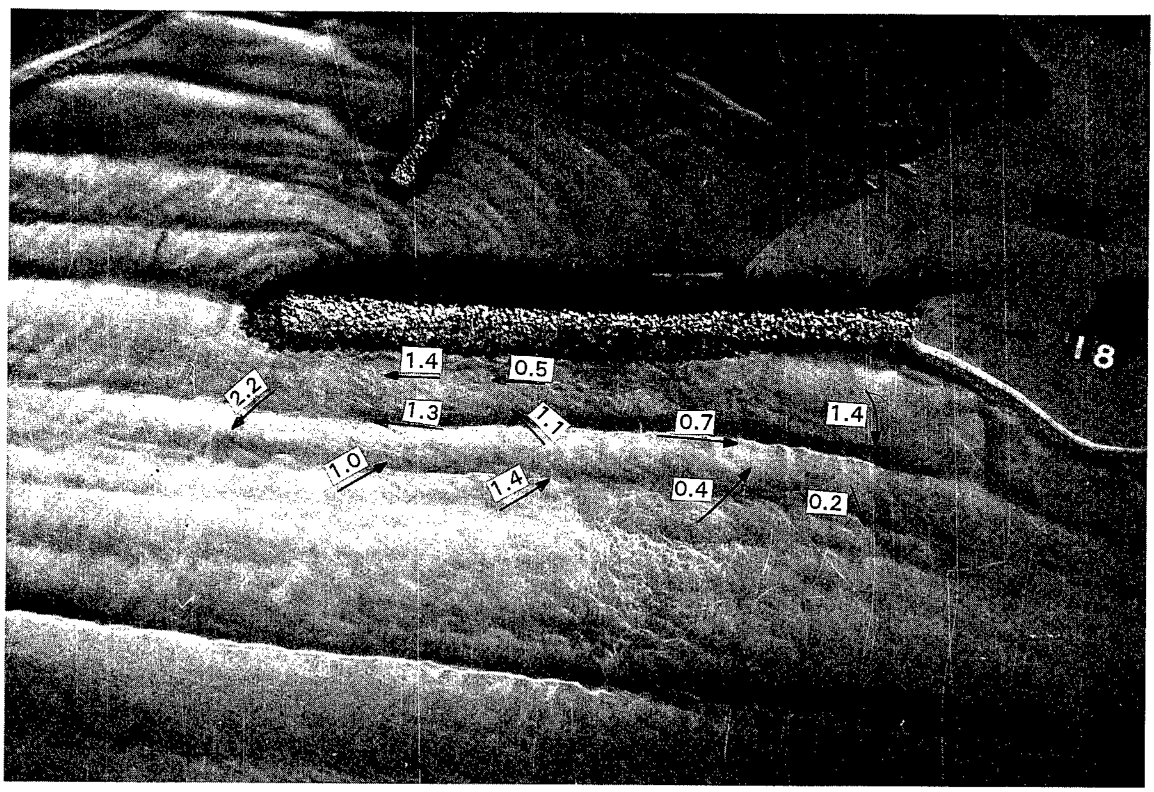


Photo 14. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for existing conditions; 16-sec, 19-ft test waves from west; swl = +7.0 ft

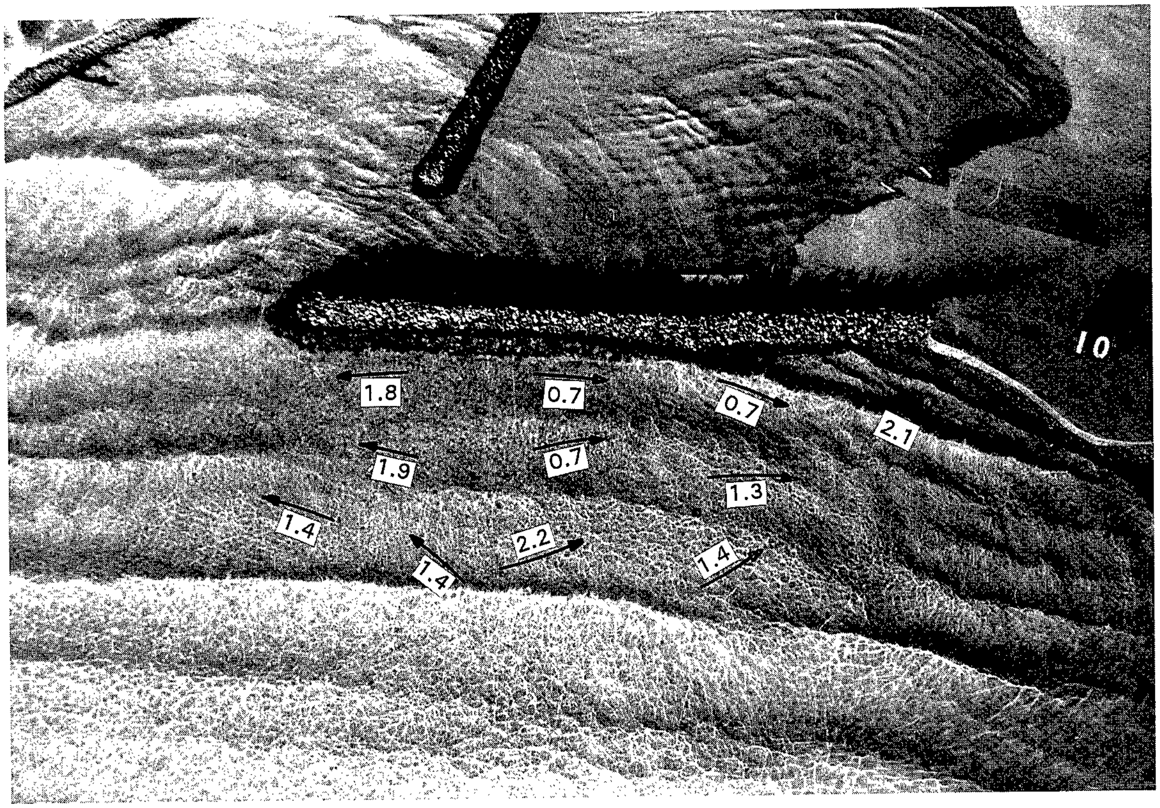


Photo 15. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for existing conditions; 20-sec, 14-ft test waves from west; swl = +7.0 ft

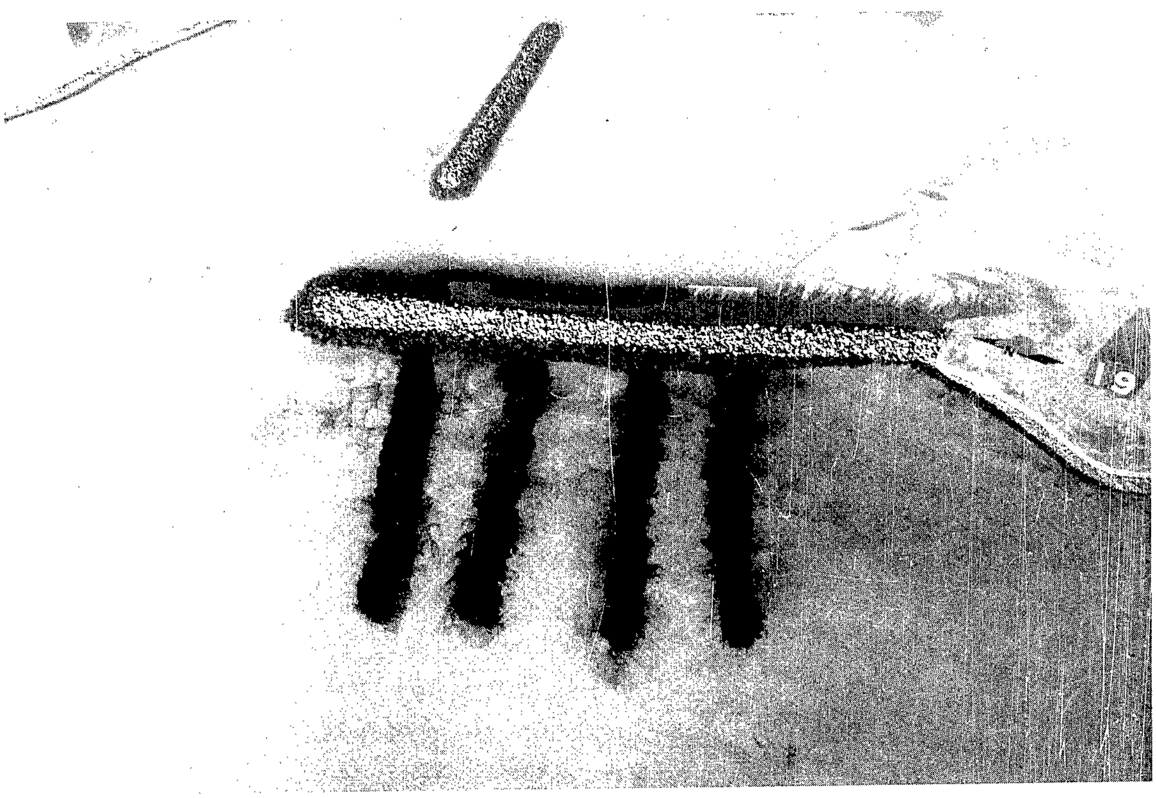


Photo 16. Placement of tracer material seaward of main breakwater for existing conditions prior to model testing

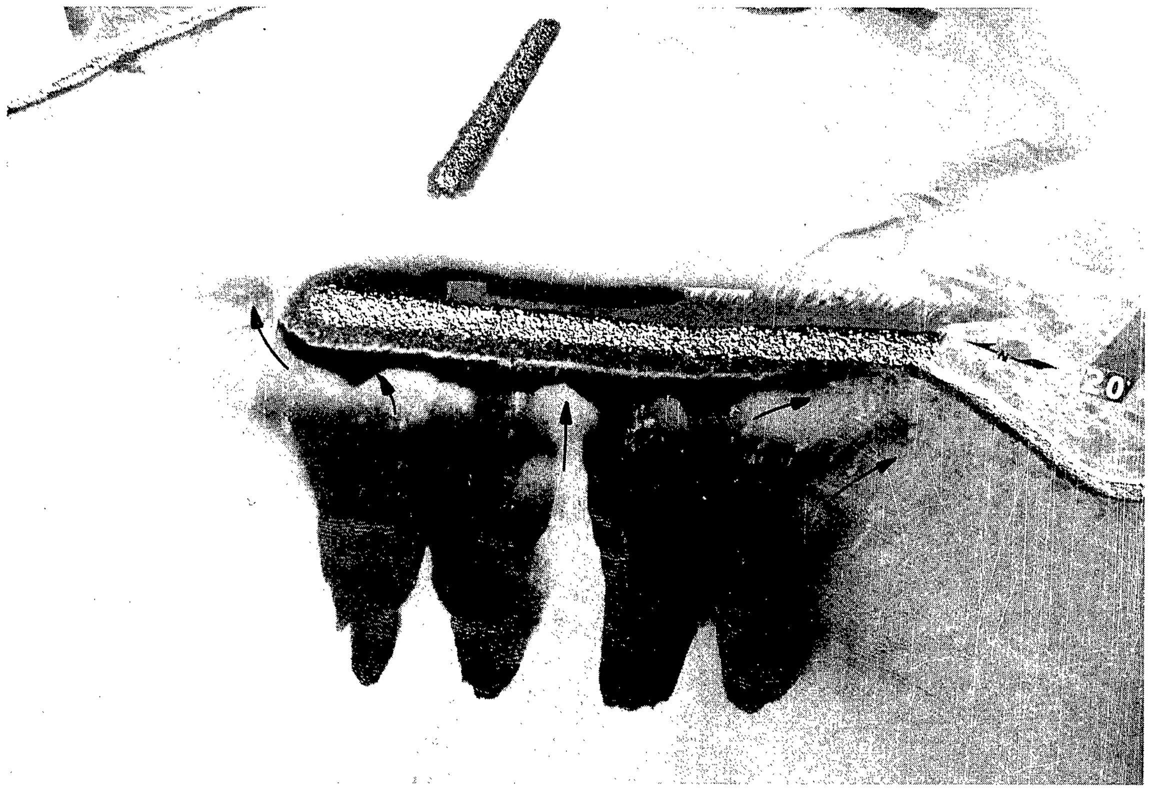


Photo 17. General movement of tracer material and subsequent deposits seaward of the main breakwater for existing conditions; 16-sec, 14.4-ft test waves from west; swl = +7.0 ft

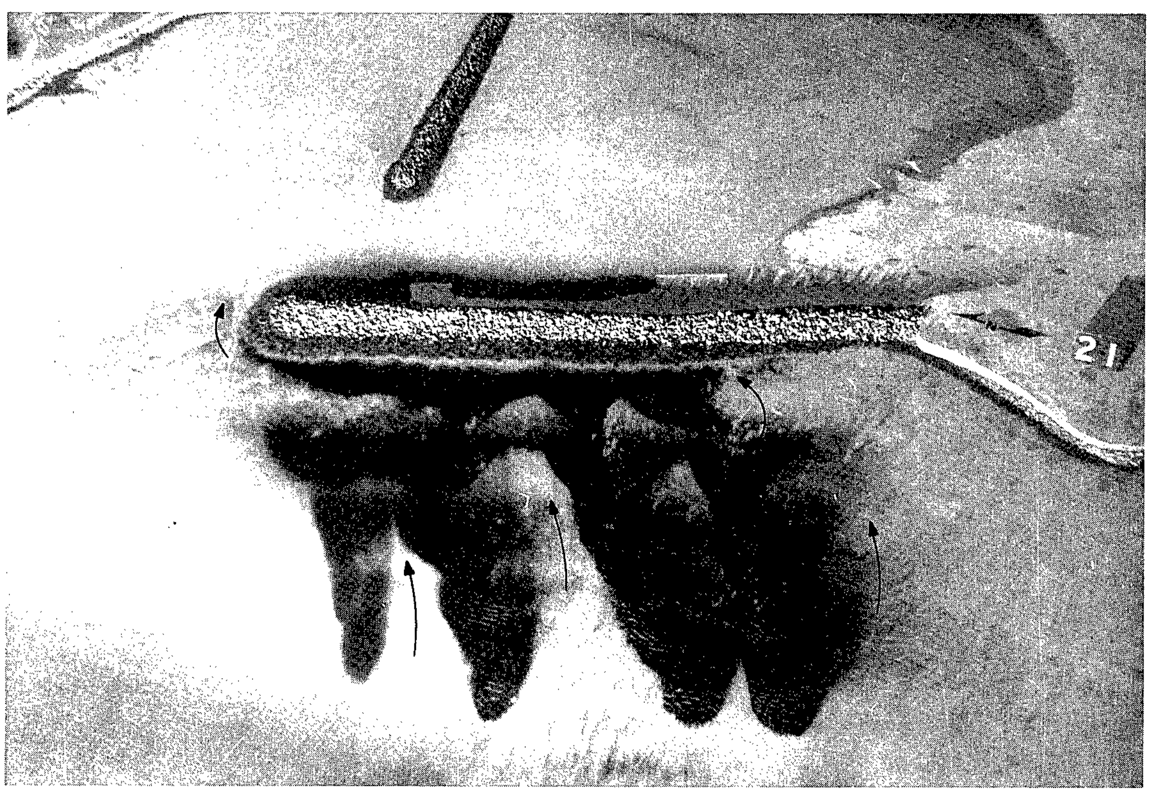


Photo 18. General movement of tracer material and subsequent deposits seaward of the main breakwater for existing conditions; 16-sec, 19-ft test waves from west; swl = +7.0 ft

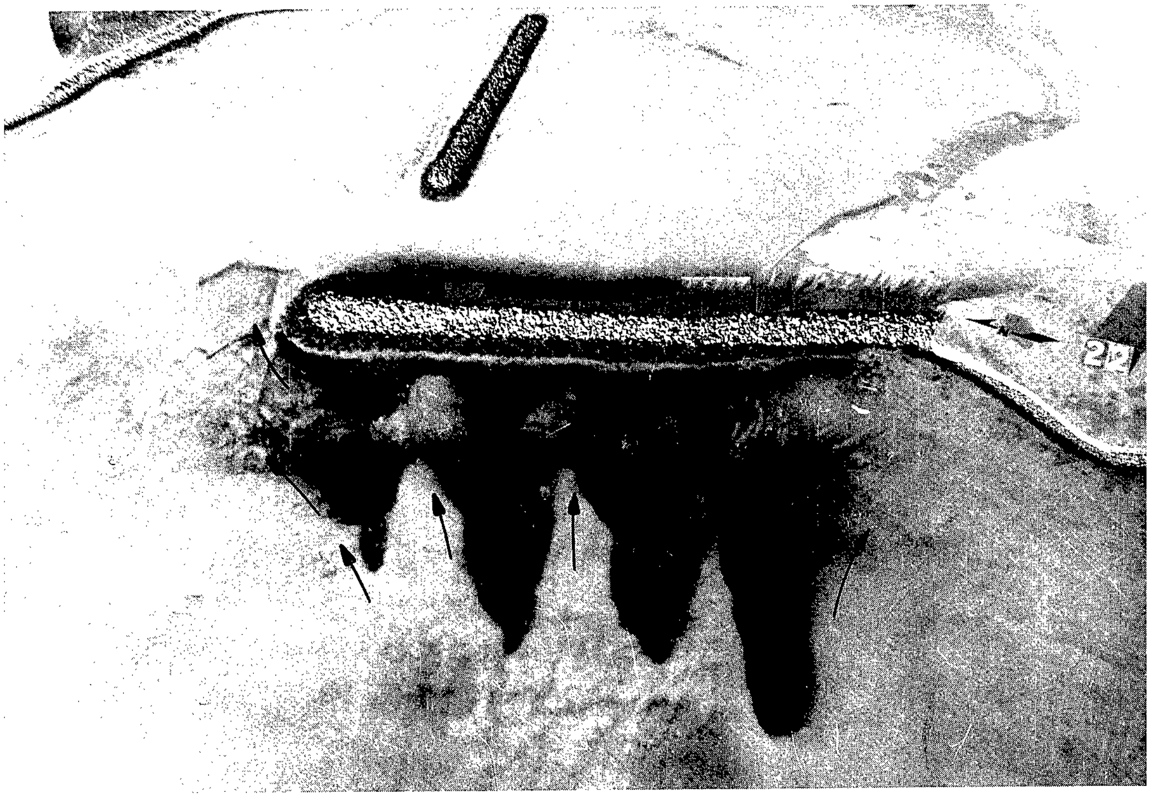


Photo 19. General movement of tracer material and subsequent deposits seaward of the main breakwater for existing conditions; 20-sec, 14-ft test waves from west; swl = +7.0 ft

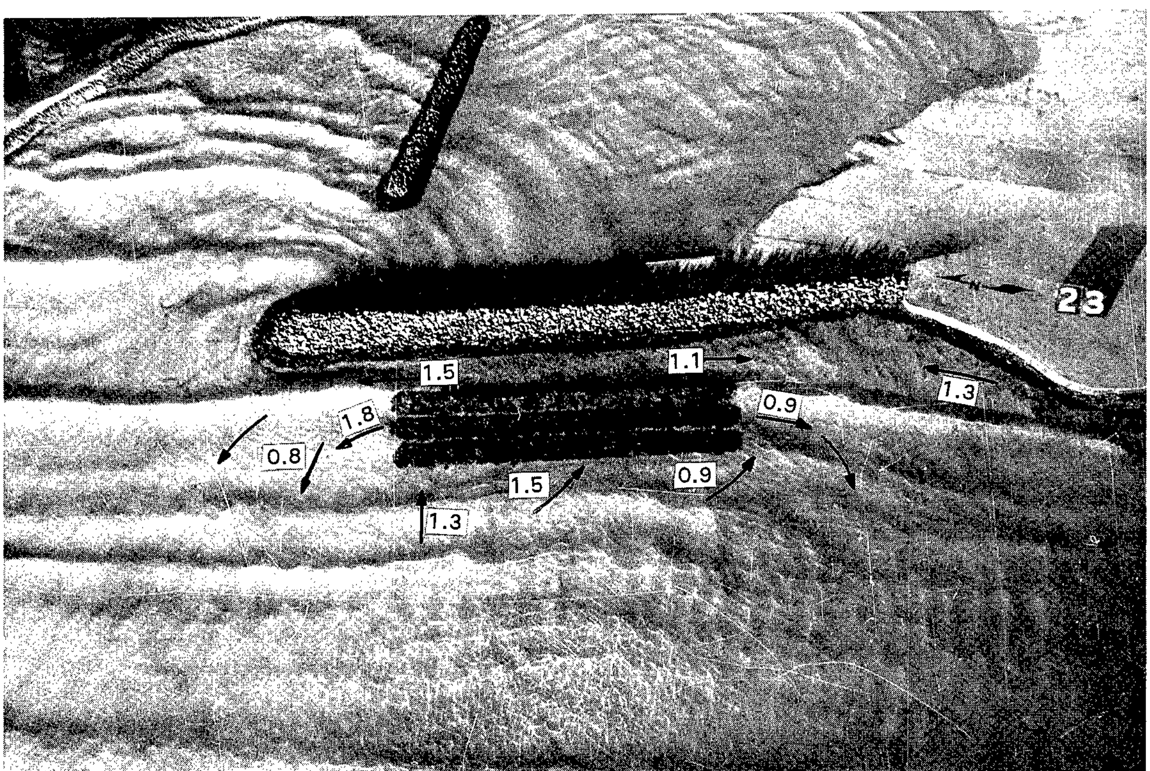


Photo 20. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 1; 16-sec, 14.4-ft test waves from west; swl = +7.0 ft

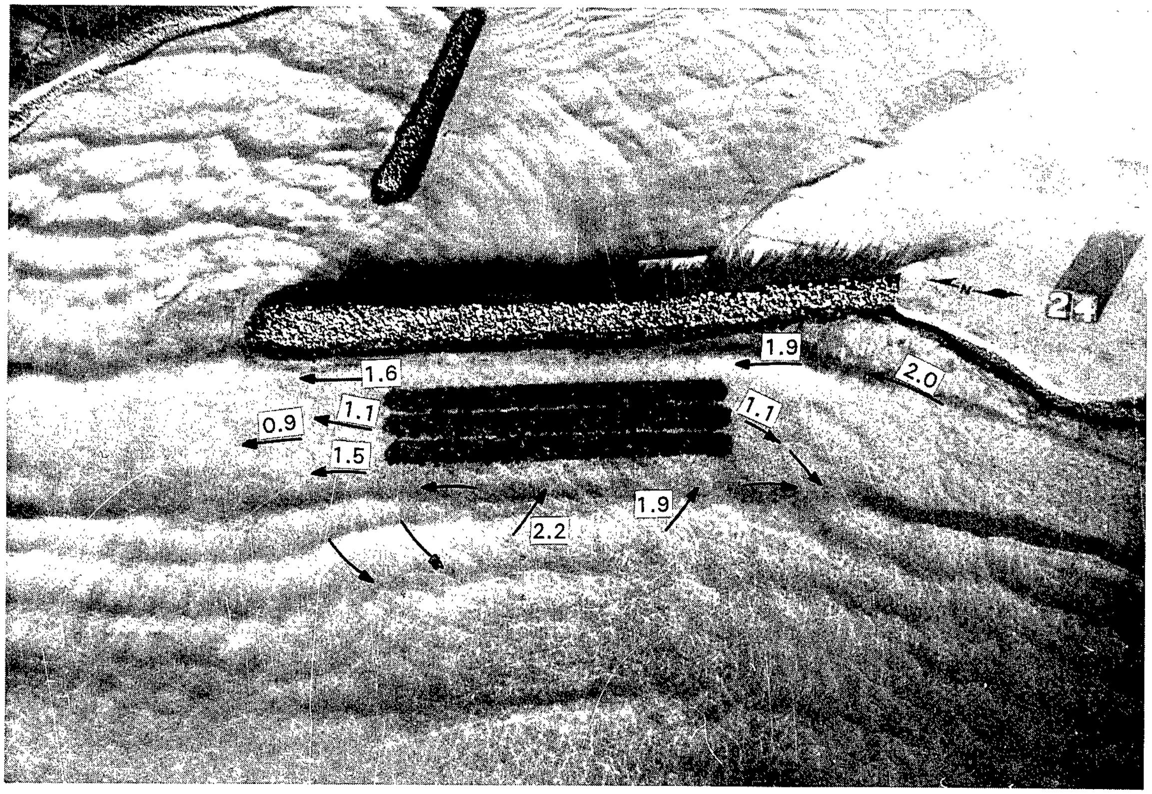


Photo 21. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 1; 16-sec, 19-ft test waves from west; swl = +7.0 ft

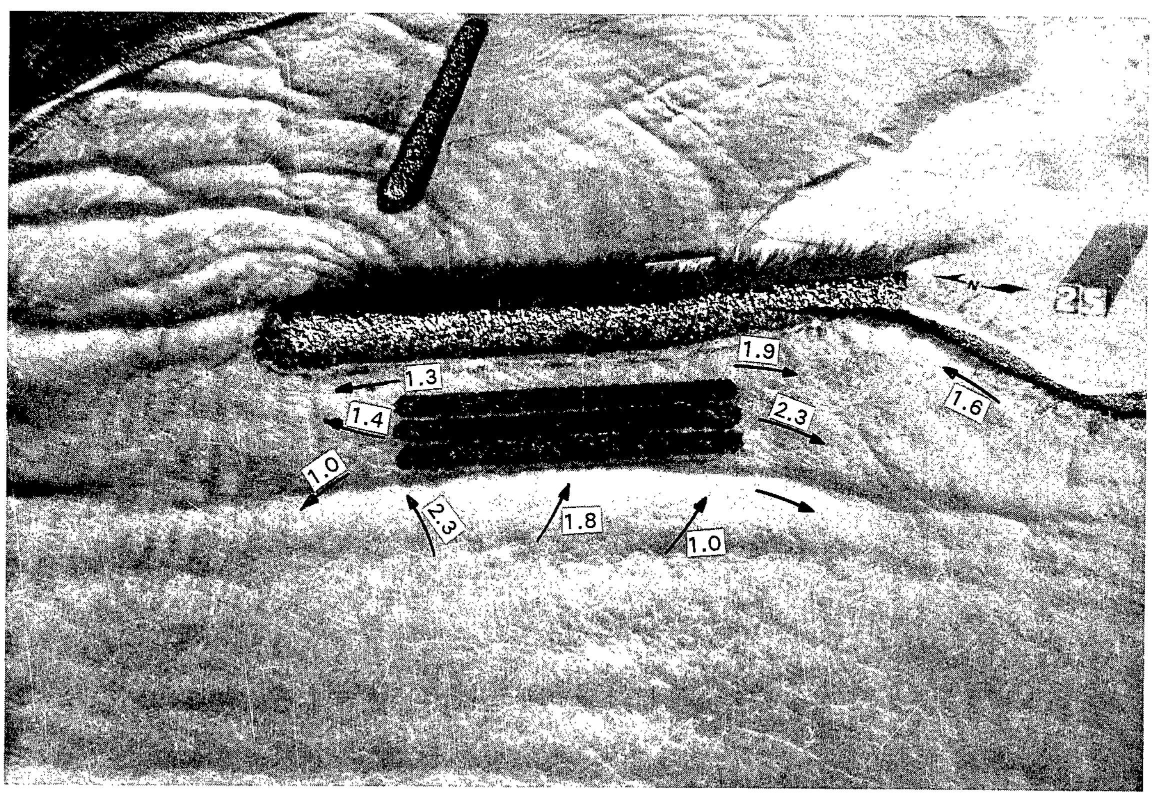


Photo 22. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 1; 20-sec, 14-ft test waves from west; swl = +7.0 ft

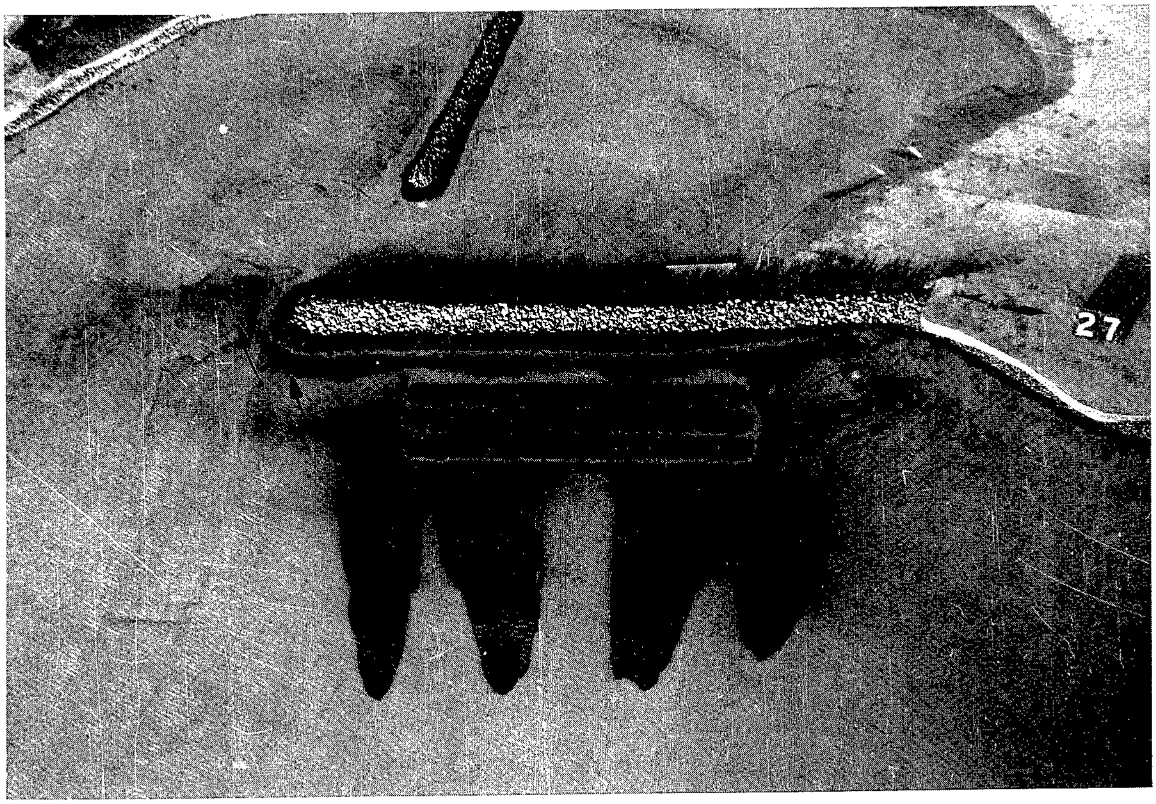


Photo 23. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 1; 16-sec, 14.4-ft test waves from west; swl = +7.0 ft

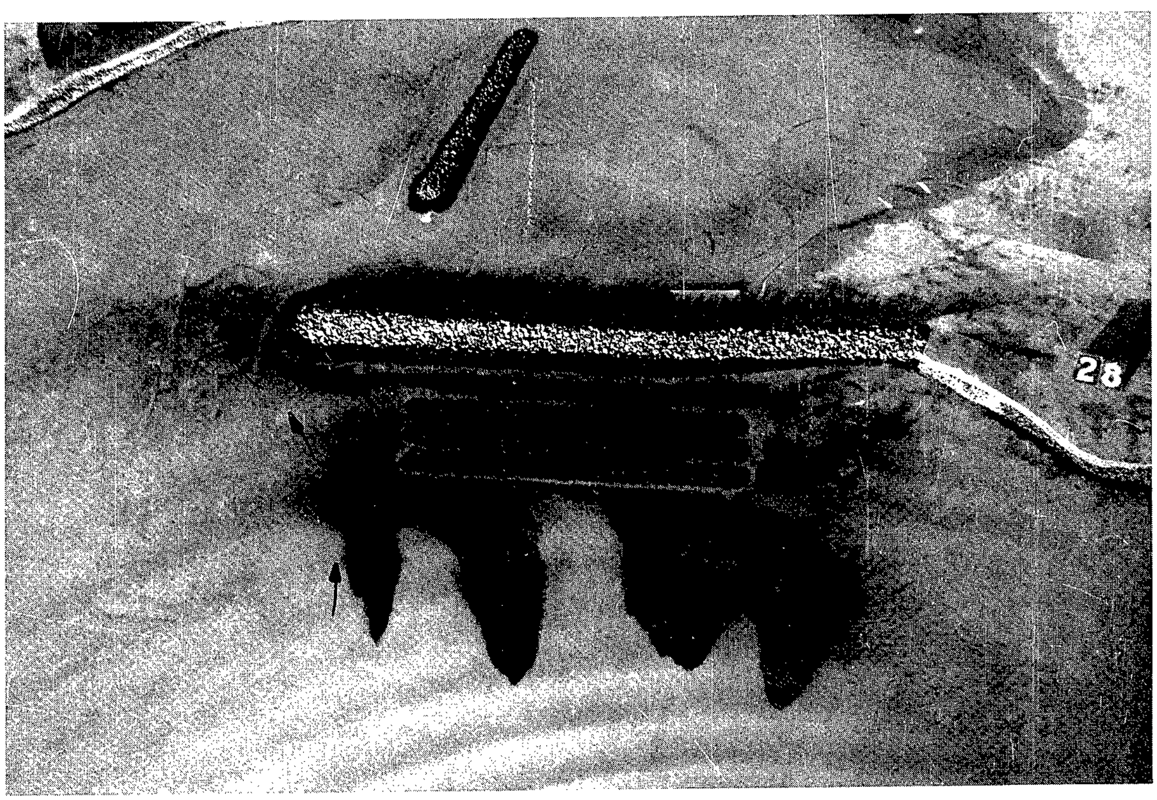


Photo 24. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 1; 16-sec, 19-ft test waves from west; swl = +7.0 ft

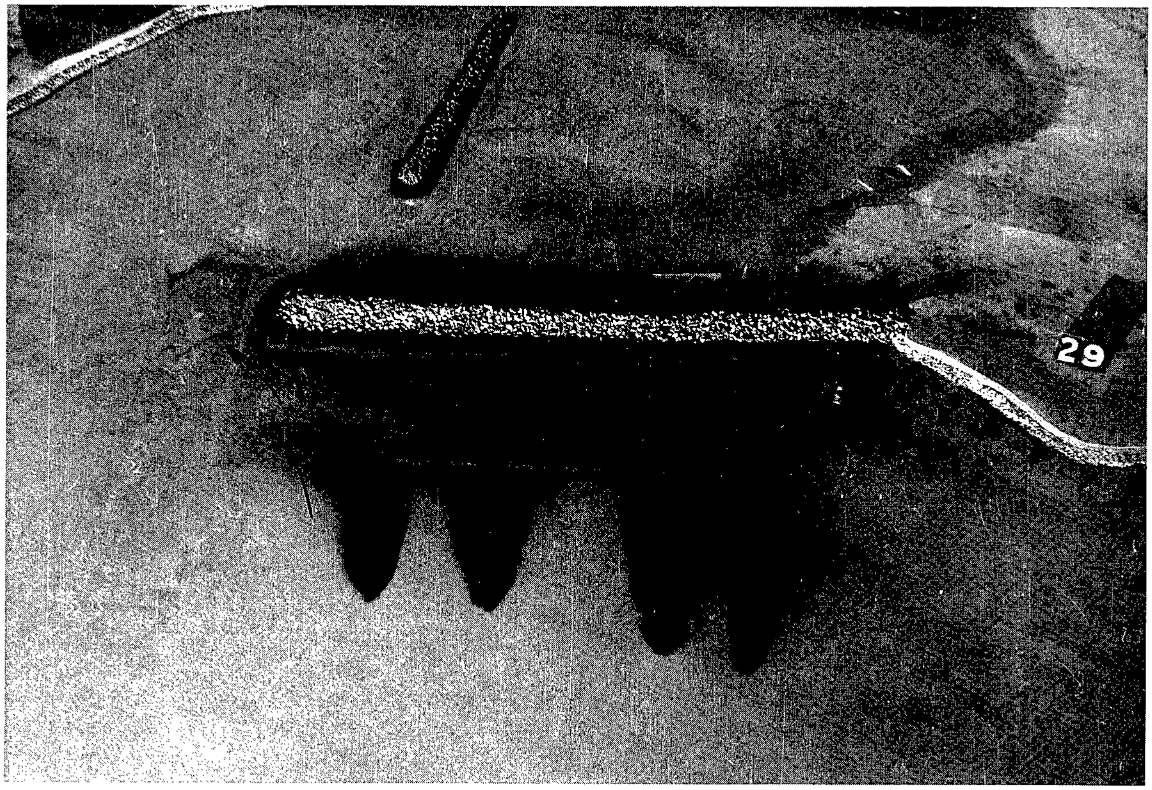


Photo 25. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 1; 20-sec, 14-ft test waves from west; swl = +7.0 ft

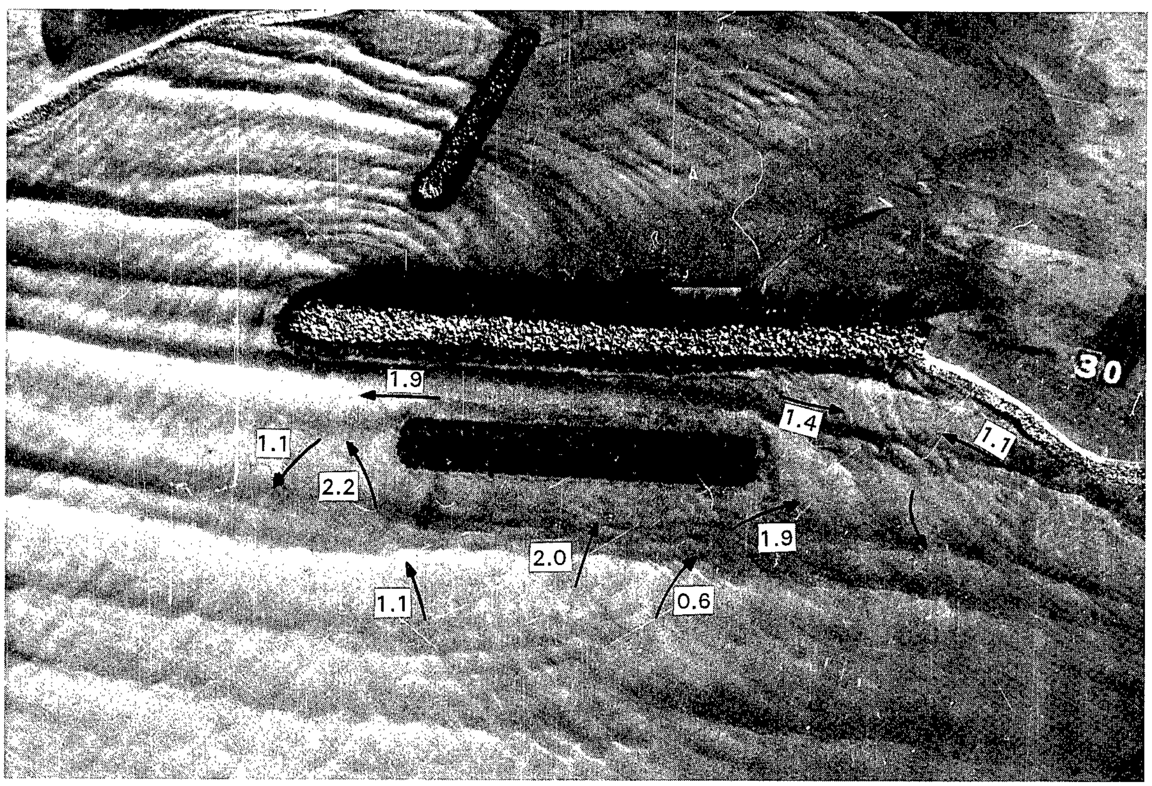


Photo 26. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 2; 16-sec, 14.4-ft test waves from west; swl = +7.0 ft

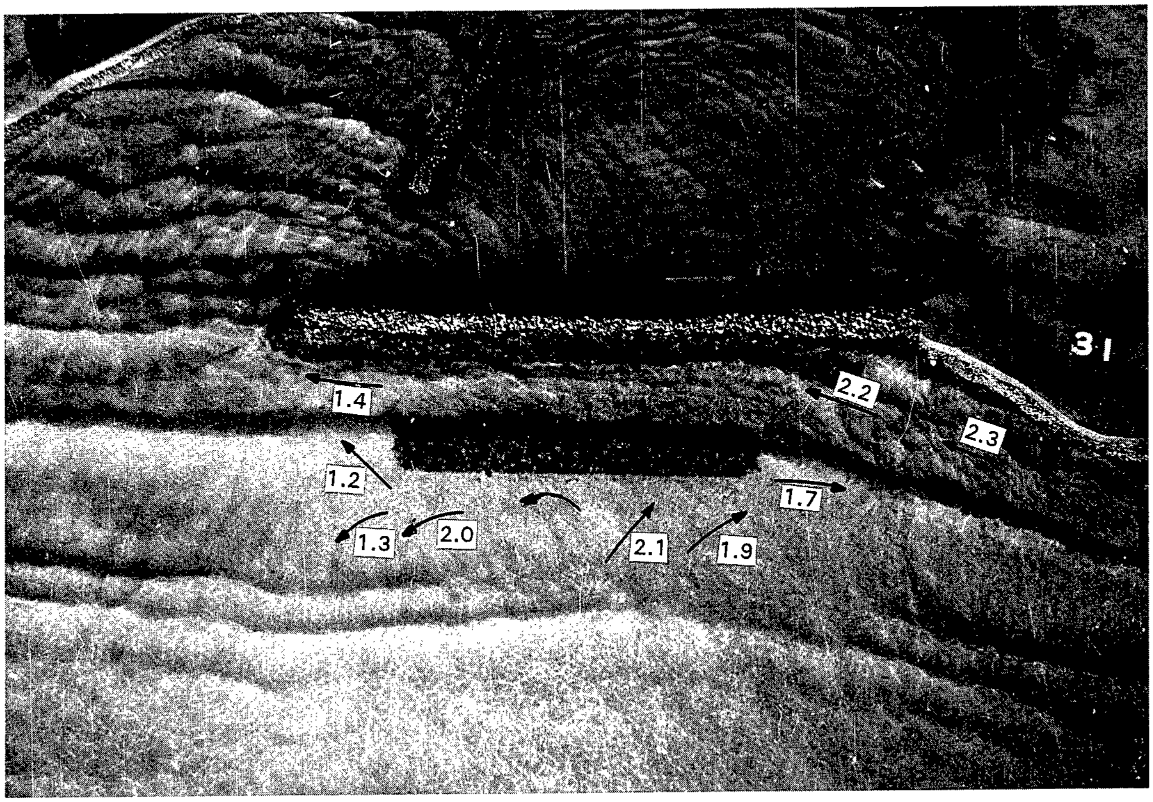


Photo 27. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 2; 16-sec, 19-ft test waves from west; swl = +7.0 ft

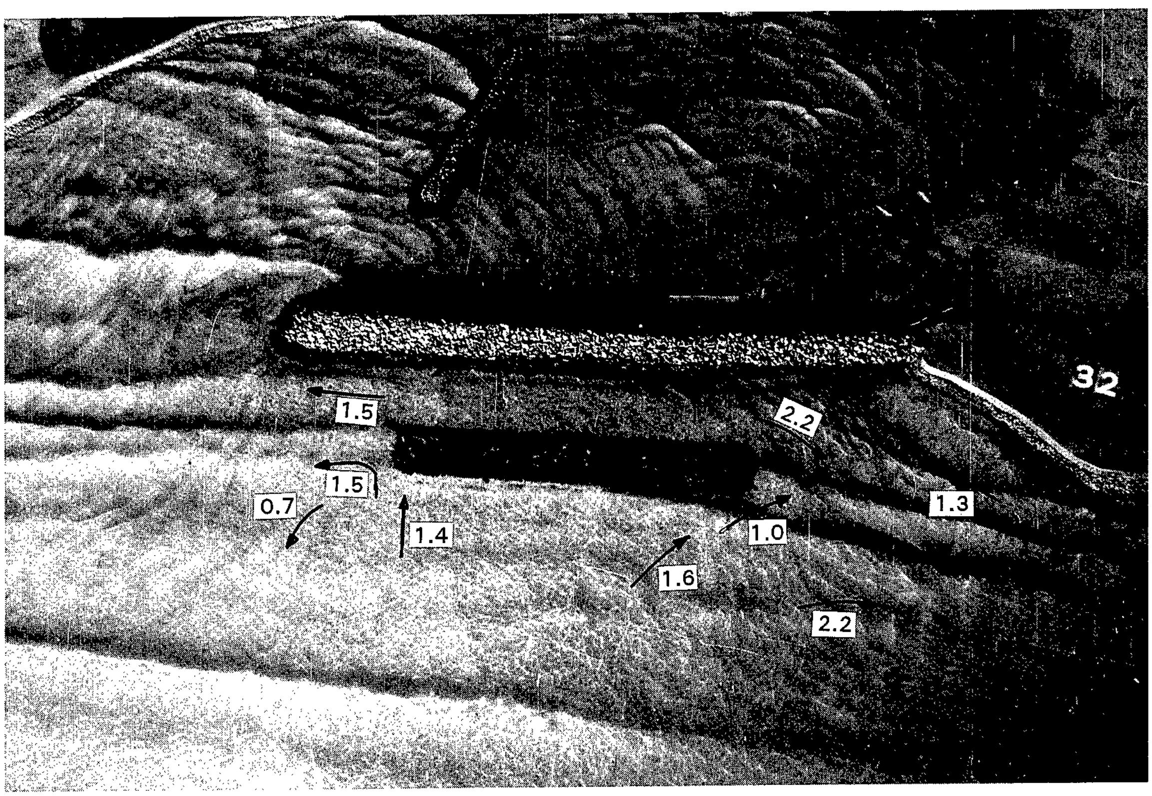


Photo 28. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 2; 20-sec, 14-ft test waves from west; swl = +7.0 ft

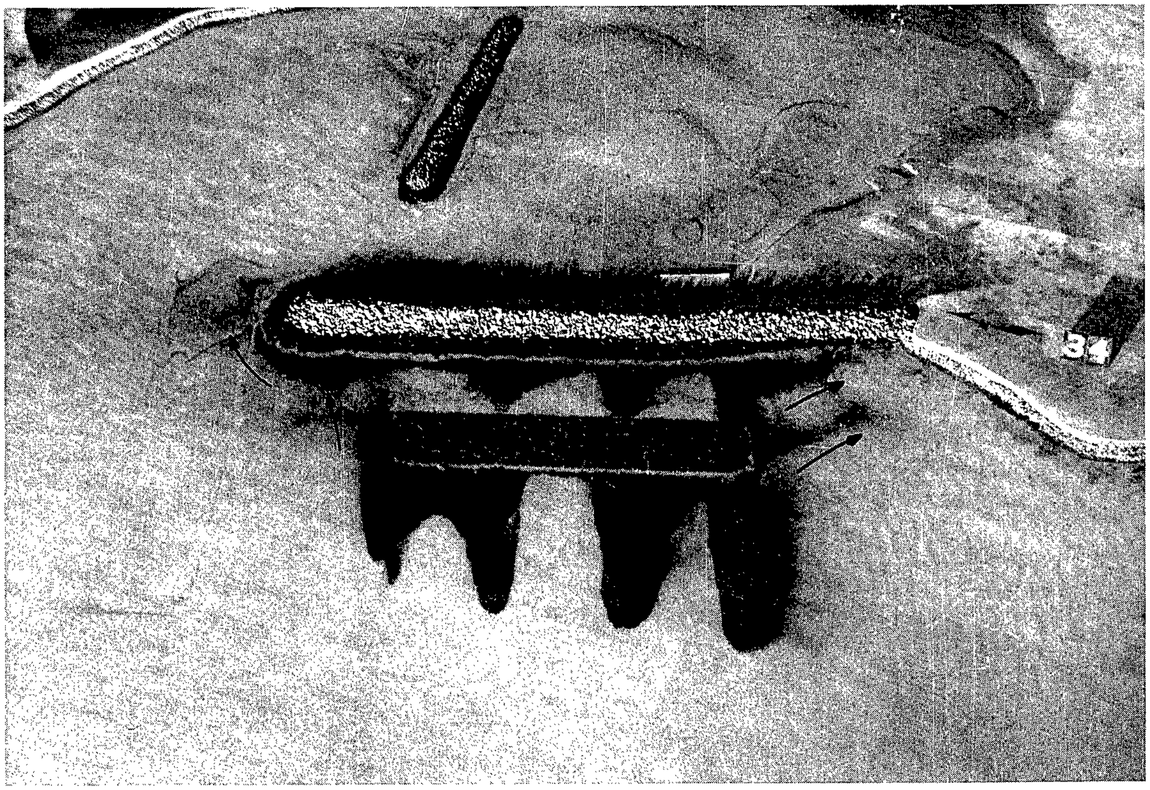


Photo 29. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 2; 16-sec, 14.4-ft test waves from west; swl = +7.0 ft

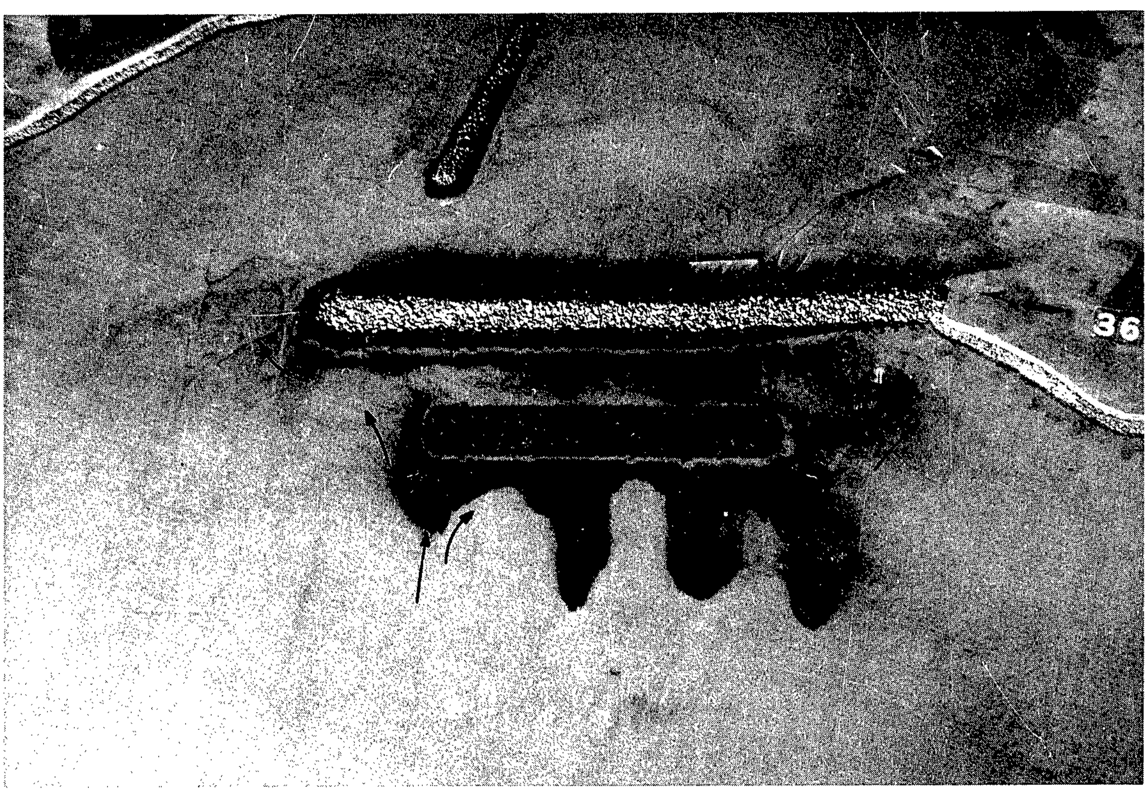


Photo 30. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 2; 16-sec, 19-ft test waves from west; swl = +7.0 ft

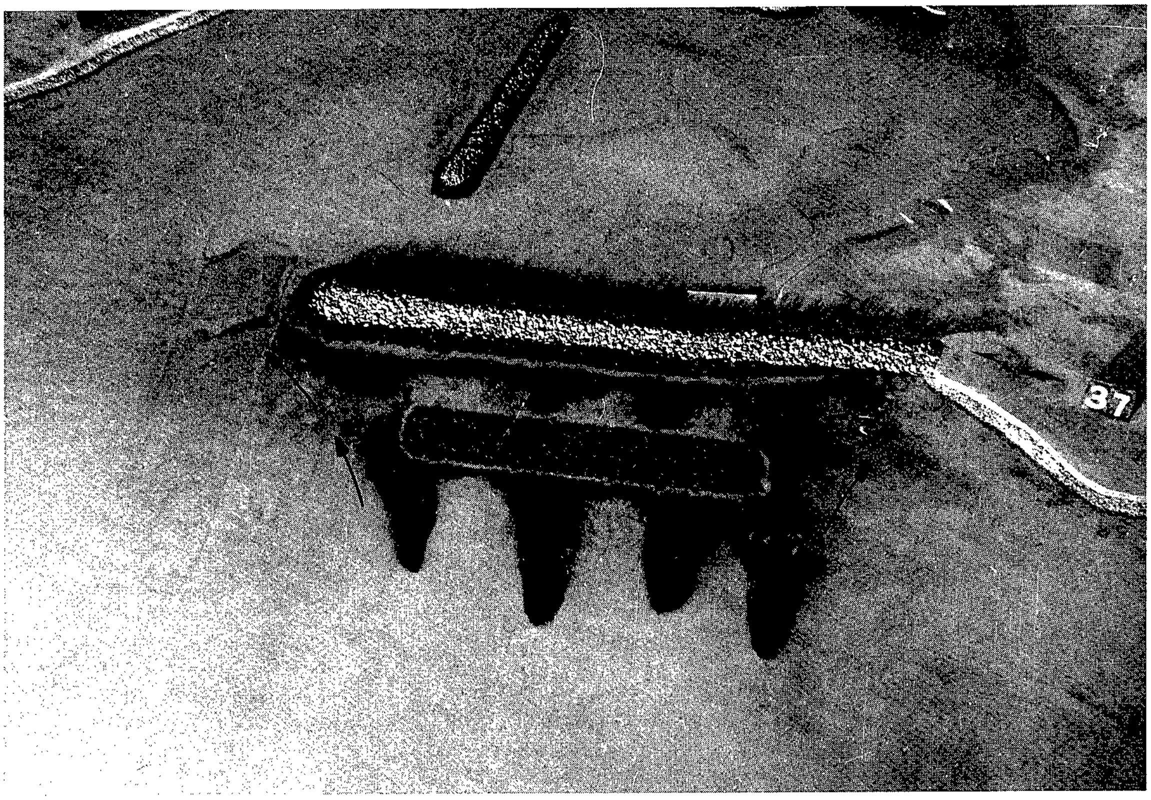


Photo 31. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 2; 20-sec, 14-ft test waves from west; swl = +7.0 ft

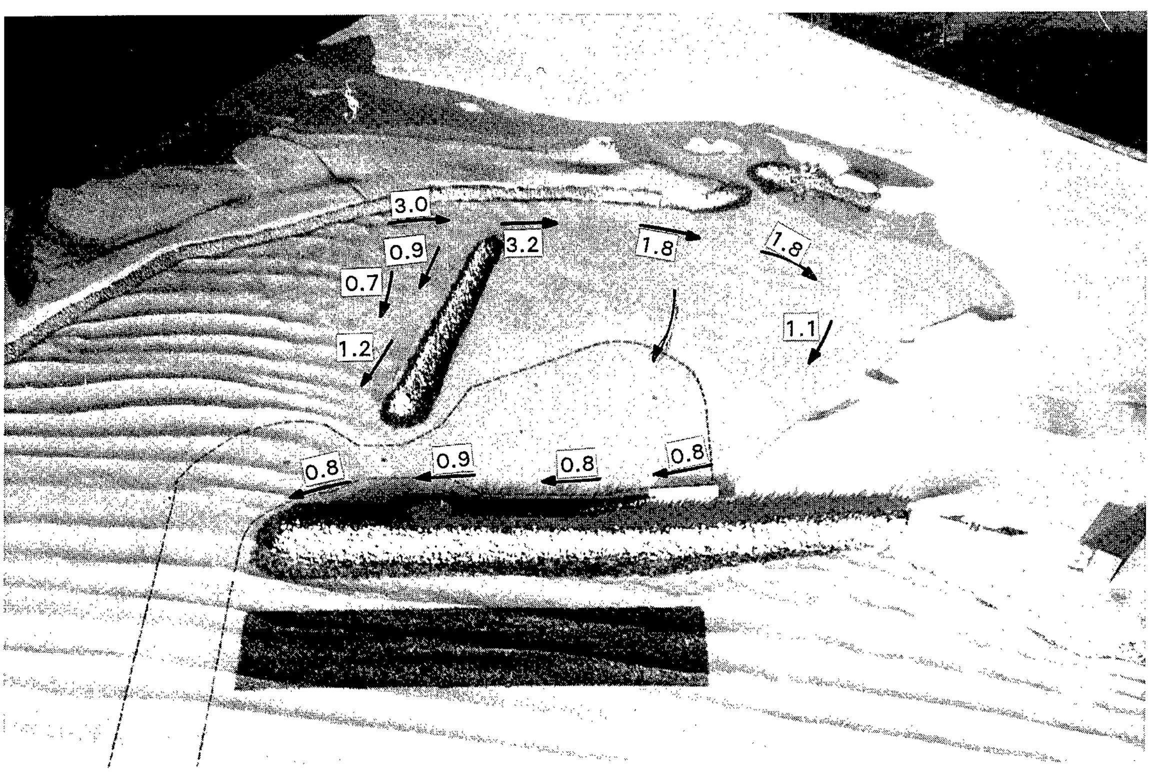


Photo 32. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 6-sec, 7-ft test waves from west; swl = +3.2 ft

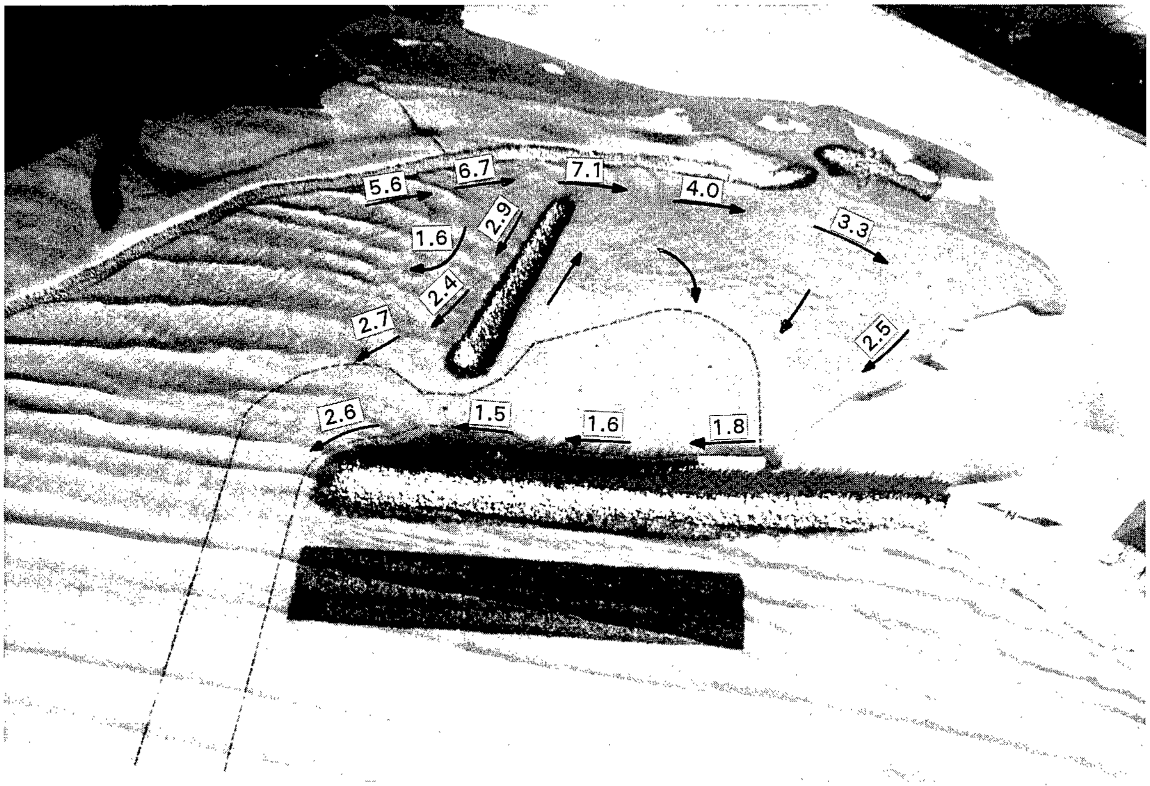


Photo 33. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 8-sec, 10-ft test waves from west; swl = +3.2 ft

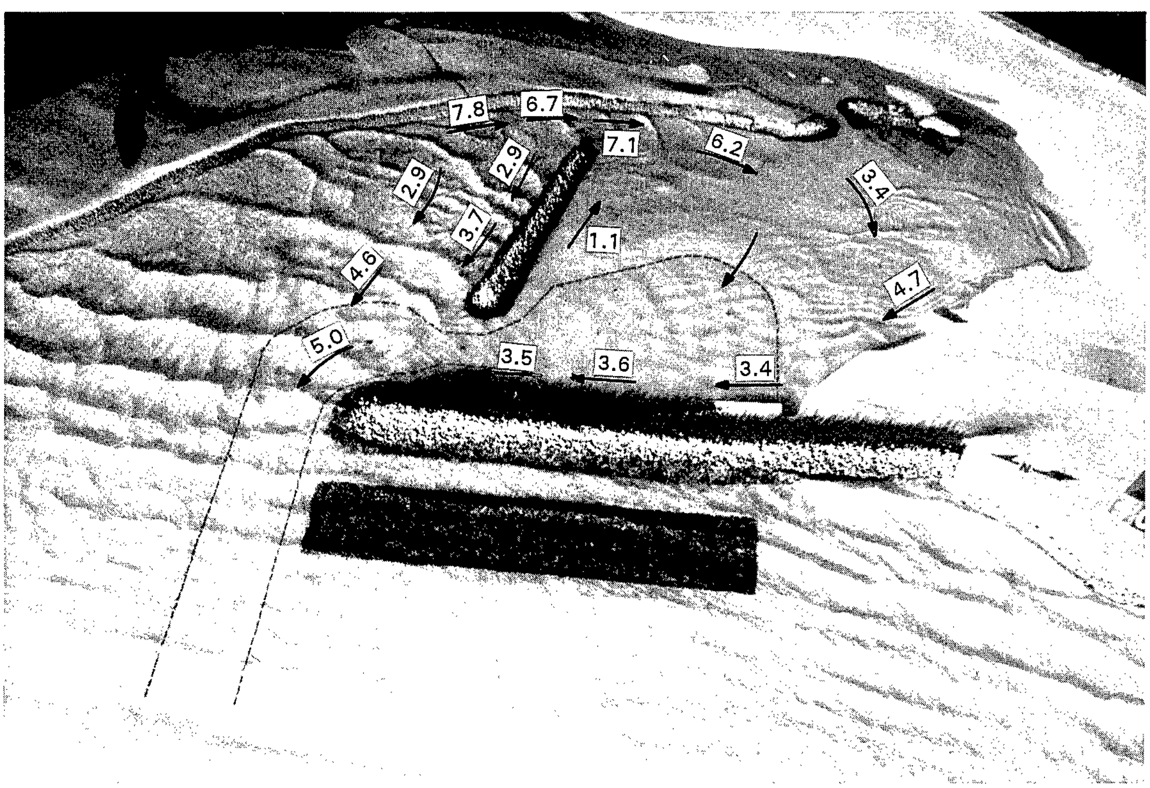


Photo 34. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 10-sec, 19-ft test waves from west; swl = +3.2 ft

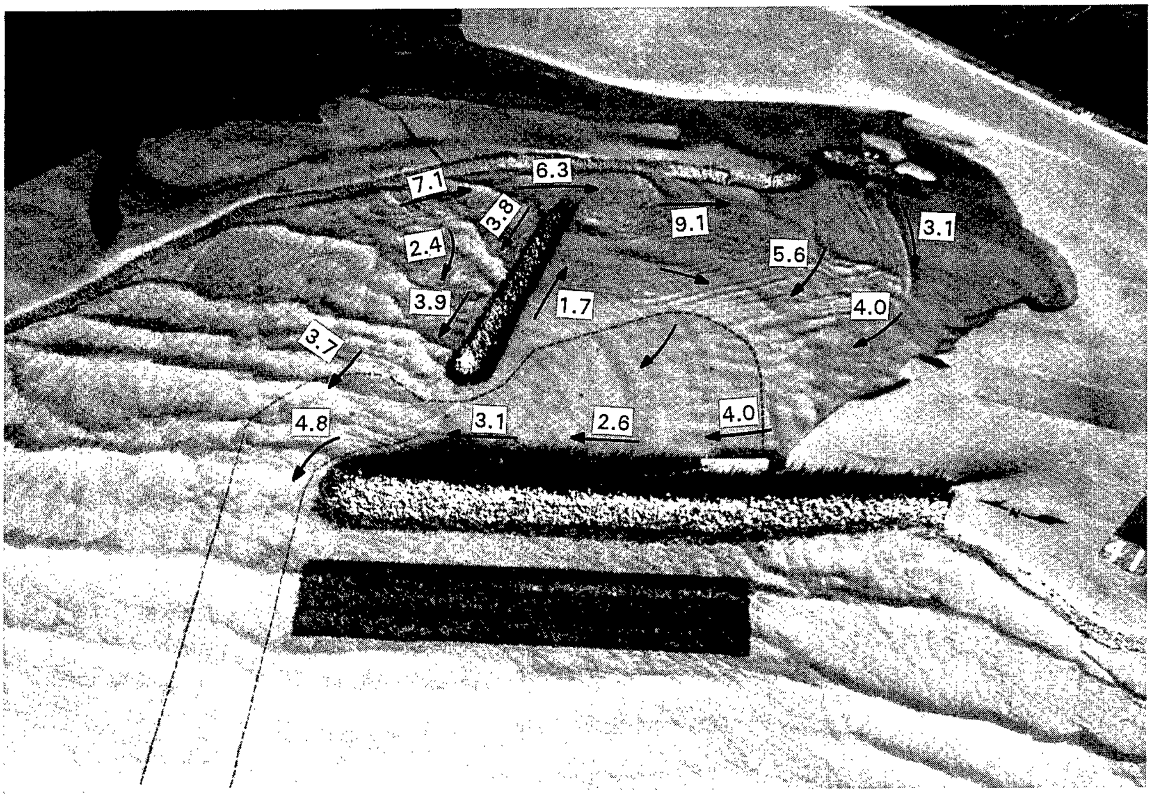


Photo 35. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 12-sec, 16-ft test waves from west; swl = +3.2 ft

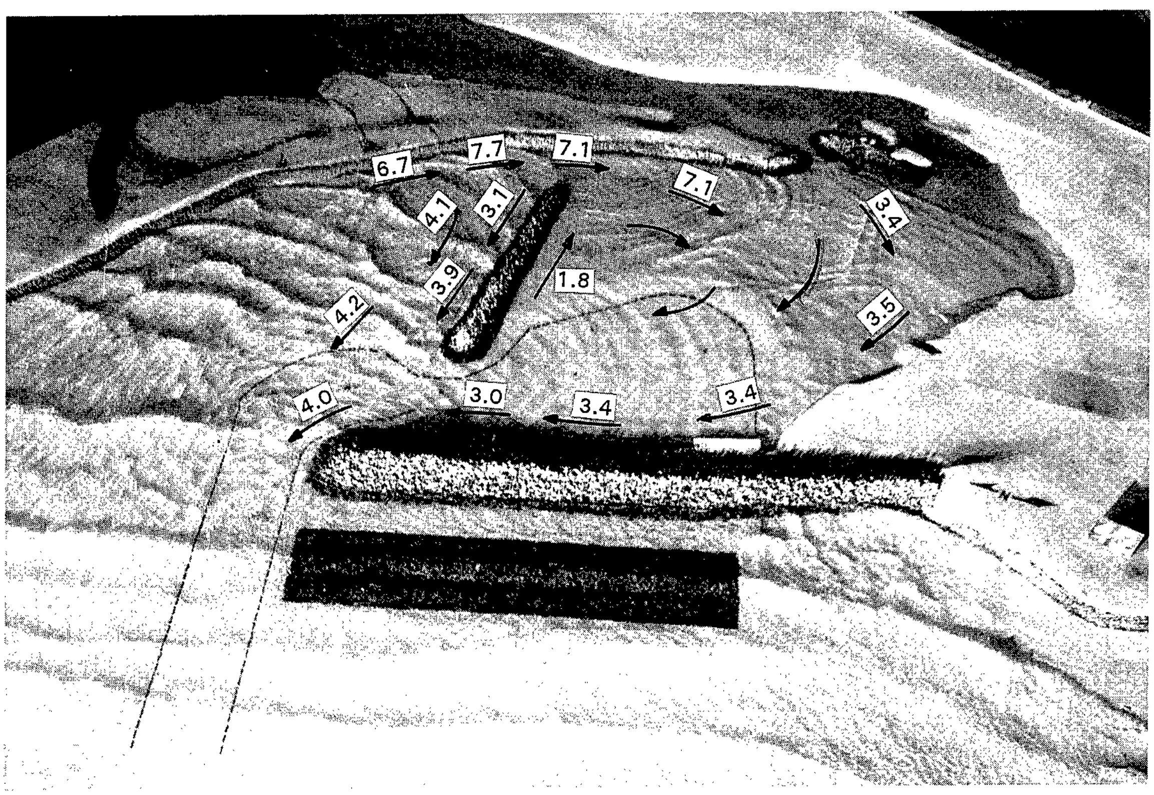


Photo 36. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 16-sec, 19-ft test waves from west; swl = +3.2 ft

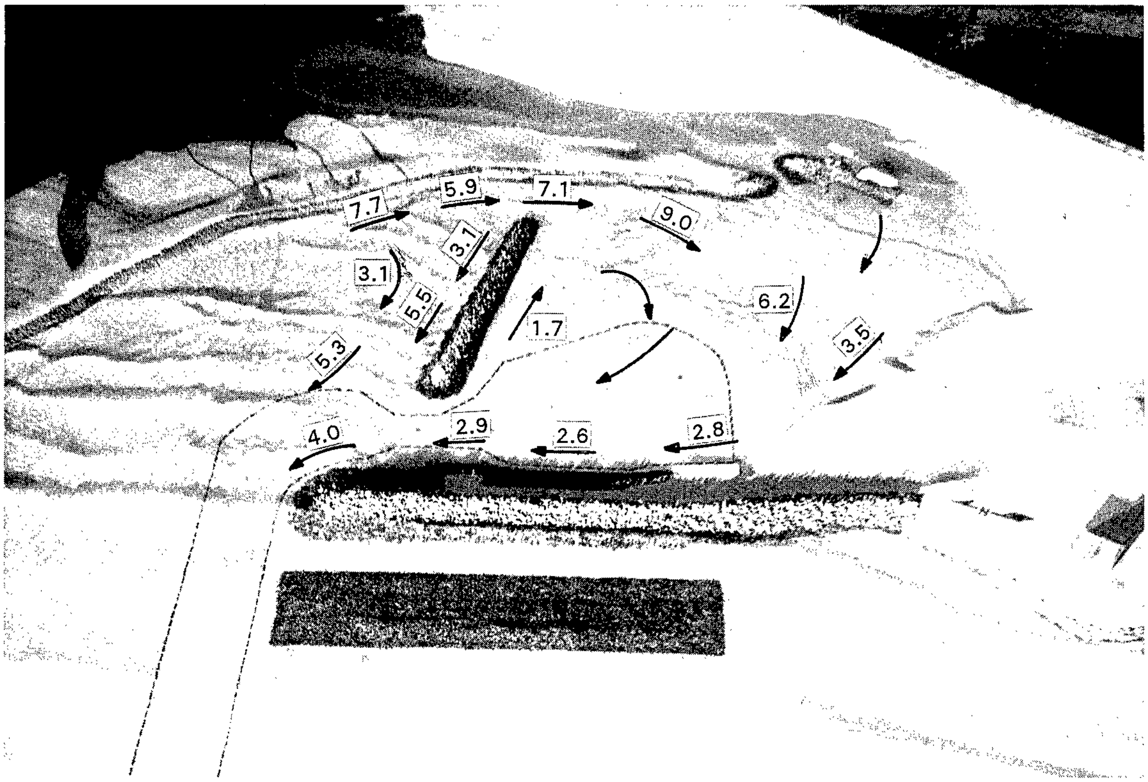


Photo 37. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 10; 20-sec, 14-ft test waves from west; swl = +3.2 ft

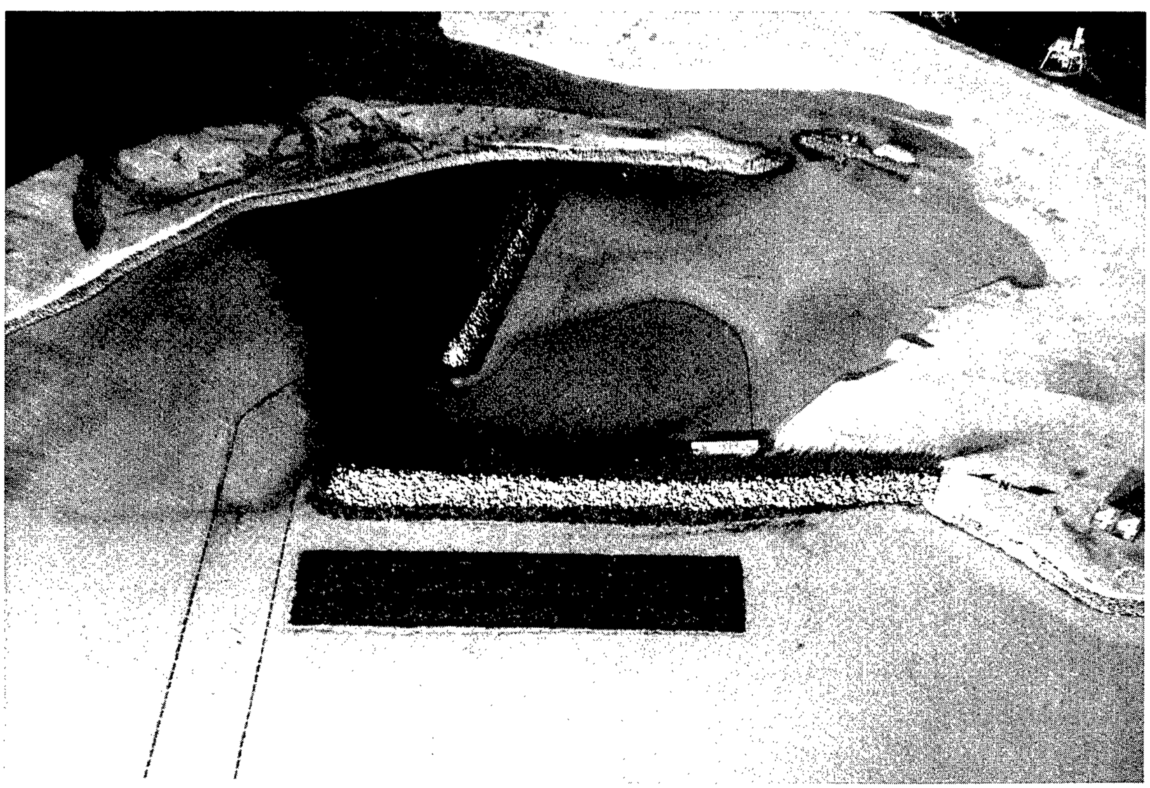


Photo 38. Placement of tracer material for Plan 10 prior to model testing

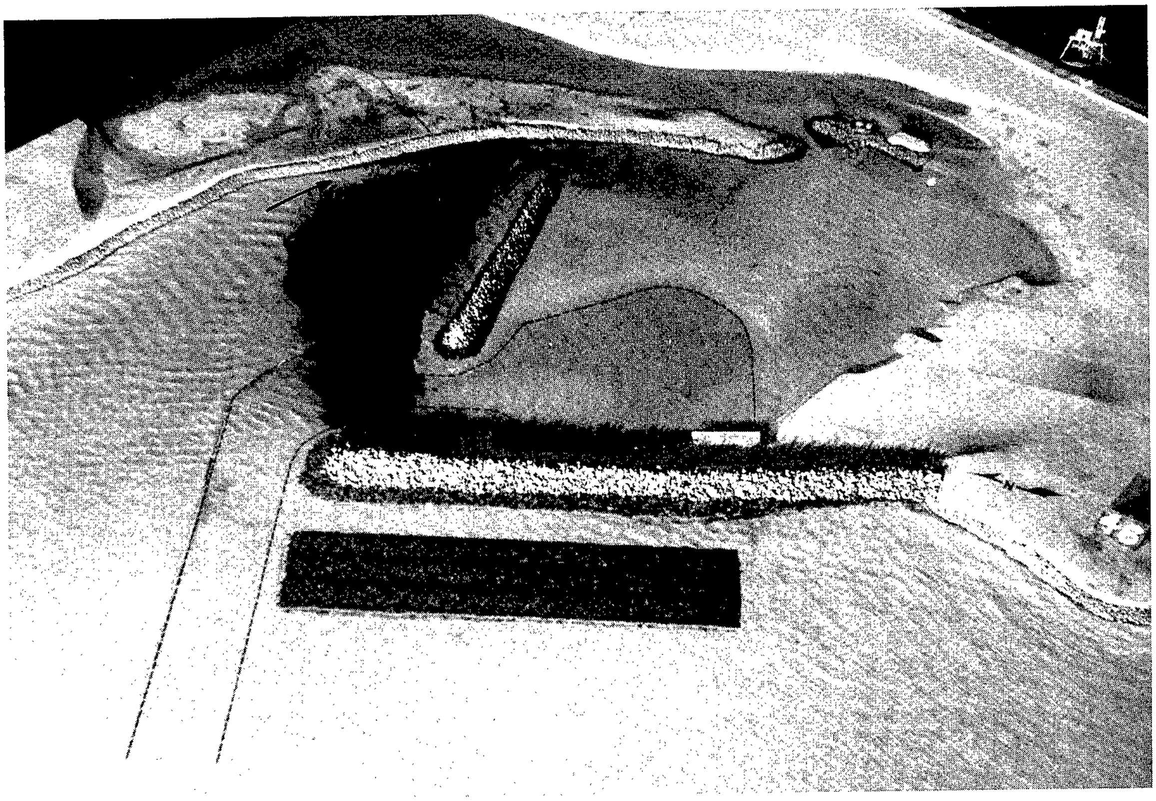


Photo 39. General movement of tracer material and subsequent deposits for Plan 10; 8-sec, 10-ft test waves from west; swl = +3.2 ft (test 1 of a series)

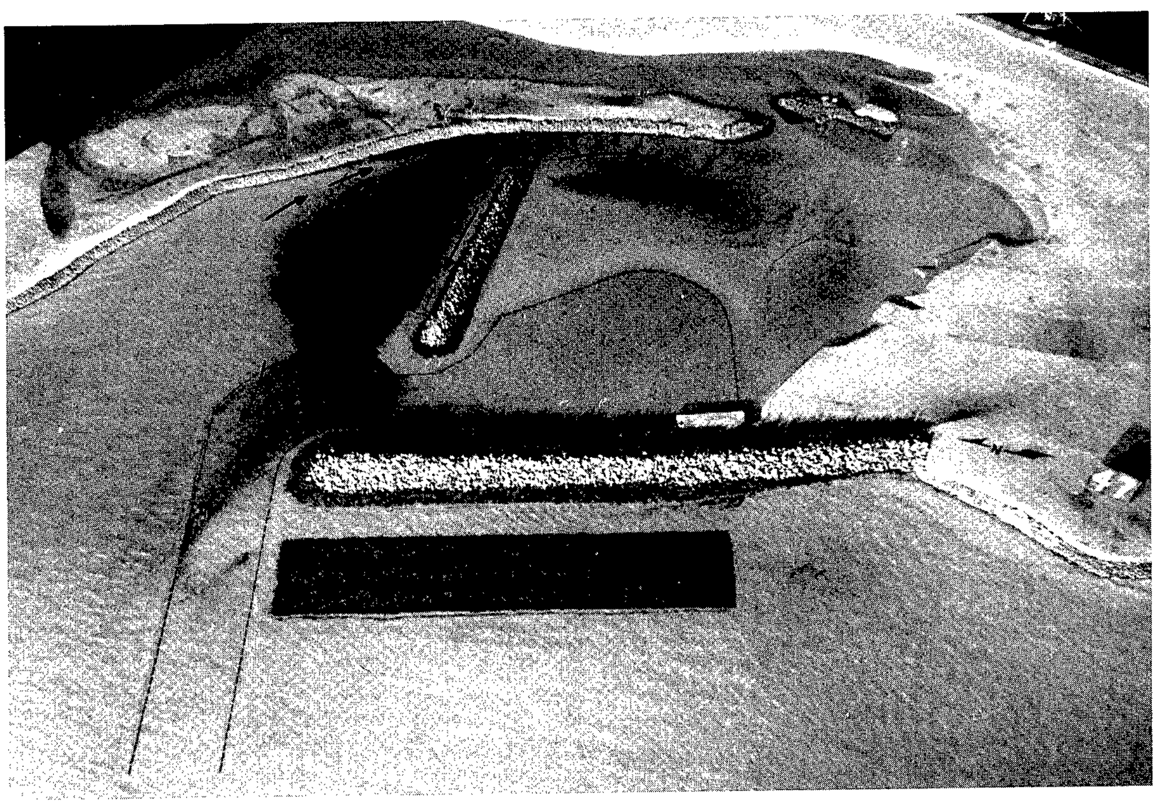


Photo 40. General movement of tracer material and subsequent deposits for Plan 10; 10-sec, 19-ft test waves from west; swl = +3.2 ft (test 2 of a series)

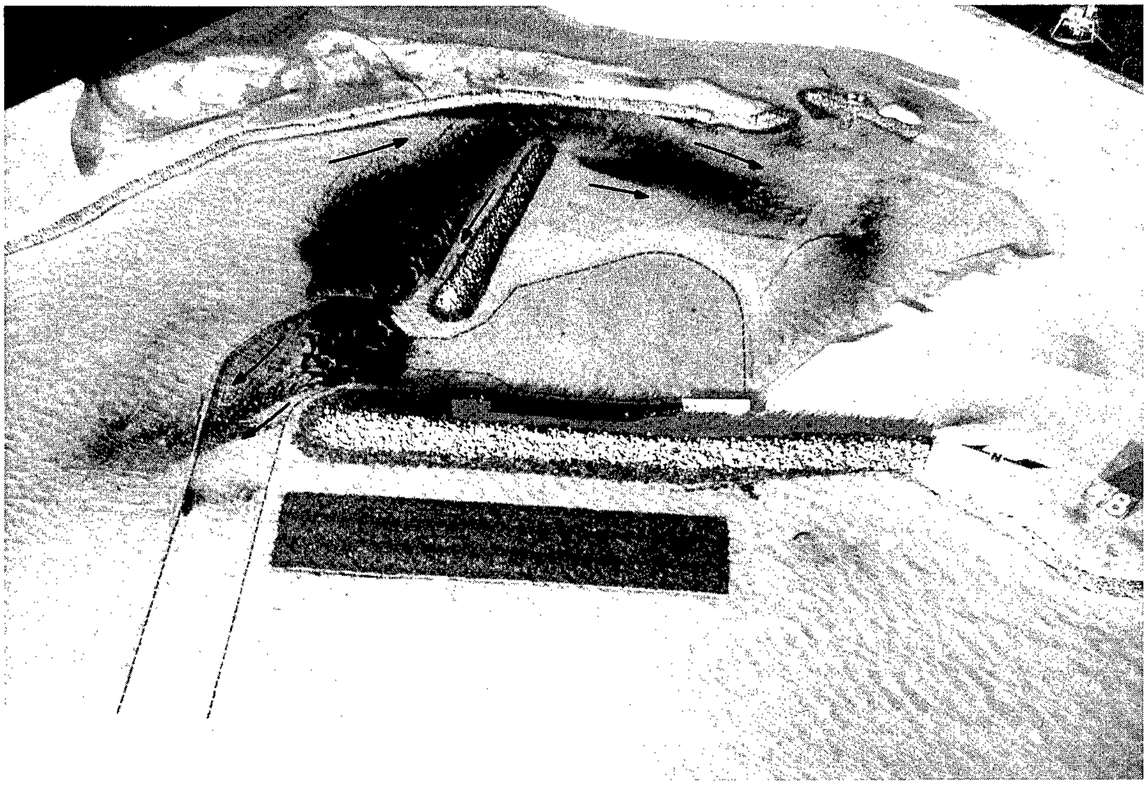


Photo 41. General movement of tracer material and subsequent deposits for Plan 10; 12-sec, 16-ft test waves from west; swl = +3.2 ft (test 3 of a series)

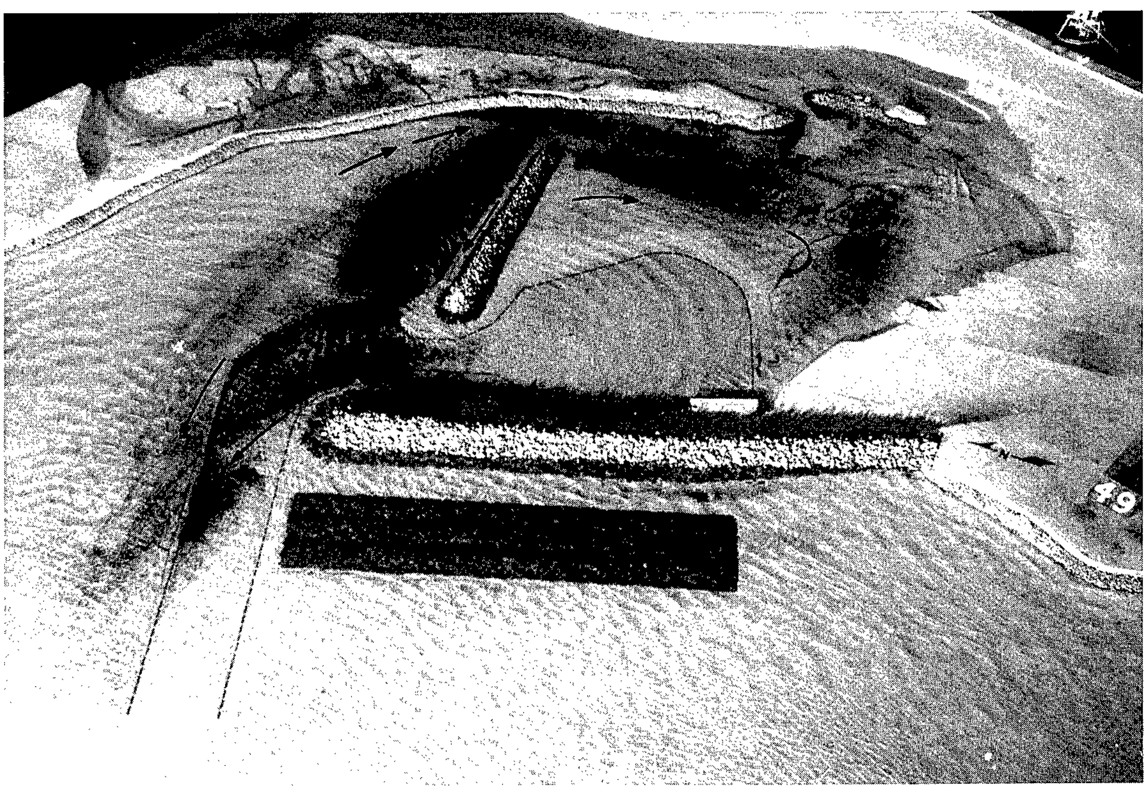


Photo 42. General movement of tracer material and subsequent deposits for Plan 10; 16-sec, 19-ft test waves from west; swl = +3.2 ft (test 4 of a series)

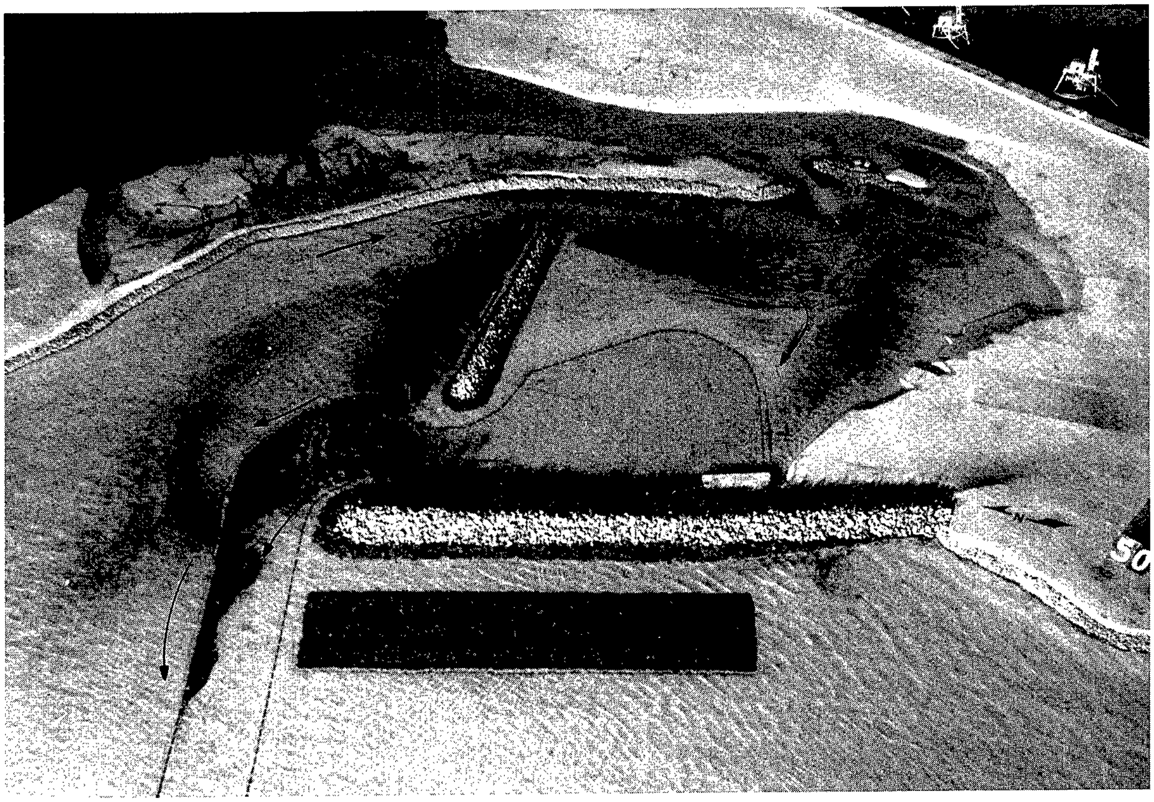


Photo 43. General movement of tracer material and subsequent deposits for Plan 10; 20-sec, 14-ft test waves from west; swl = +3.2 ft (test 5 of a series)

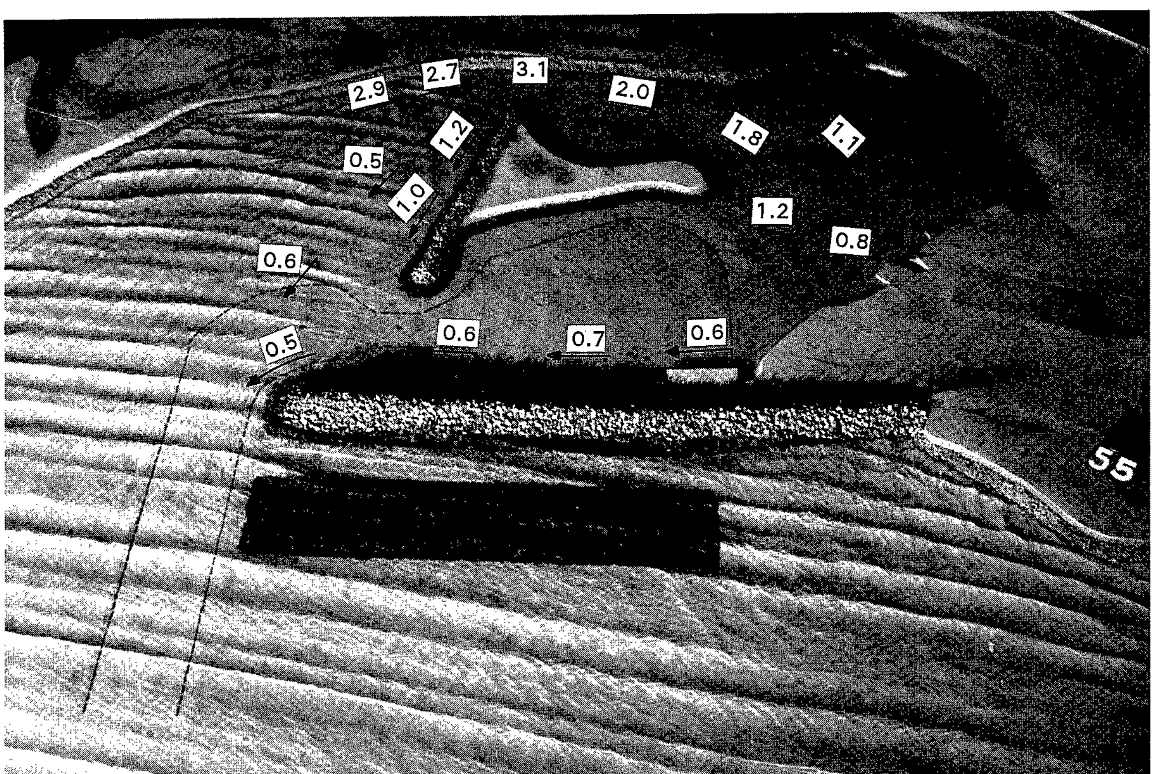


Photo 44. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 11; 6-sec, 7-ft test waves from west; swl = +3.2 ft

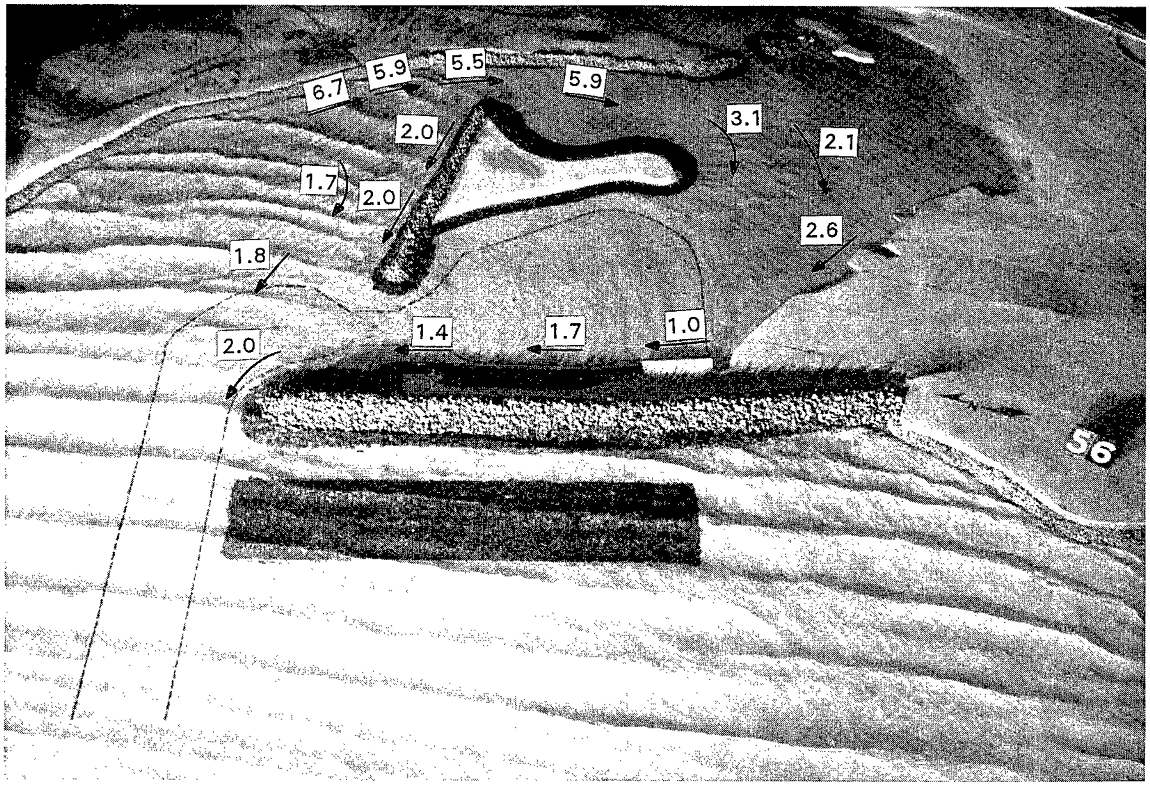


Photo 45. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 11; 8-sec, 10-ft test waves from west; swl = +3.2 ft

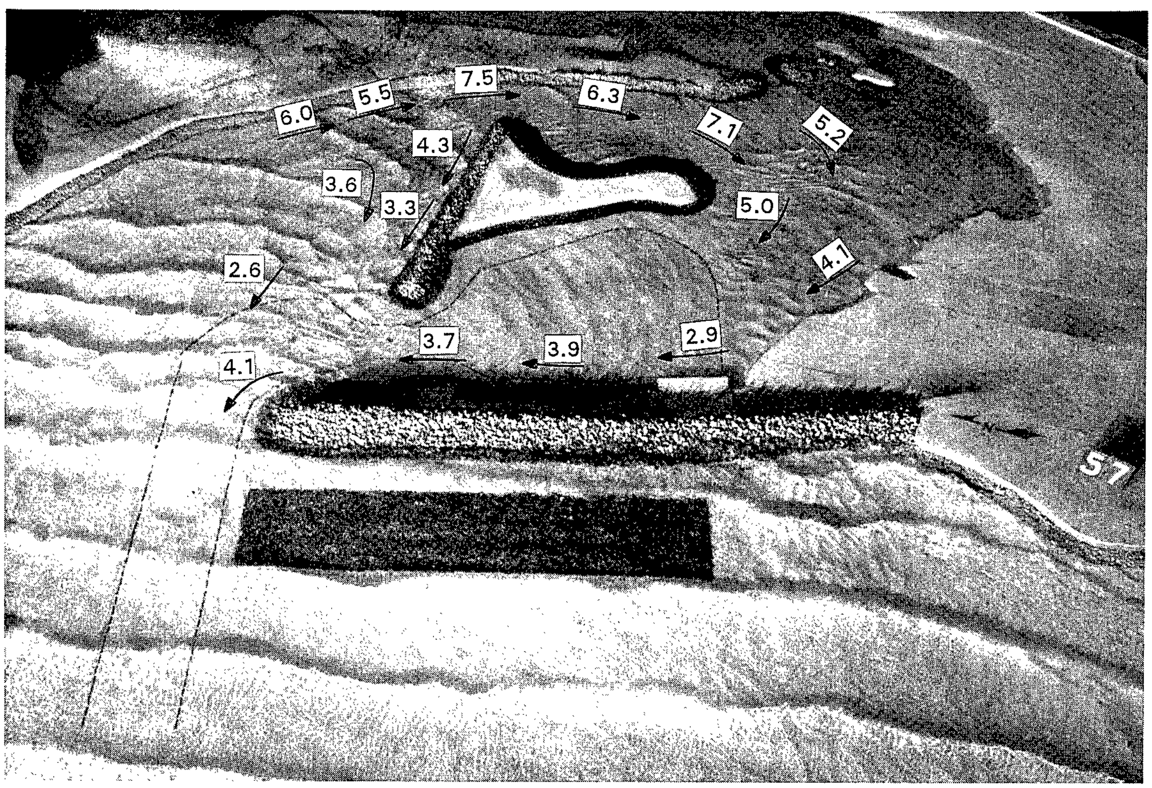


Photo 46. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 11; 10-sec, 19-ft test waves from west; swl = +3.2 ft

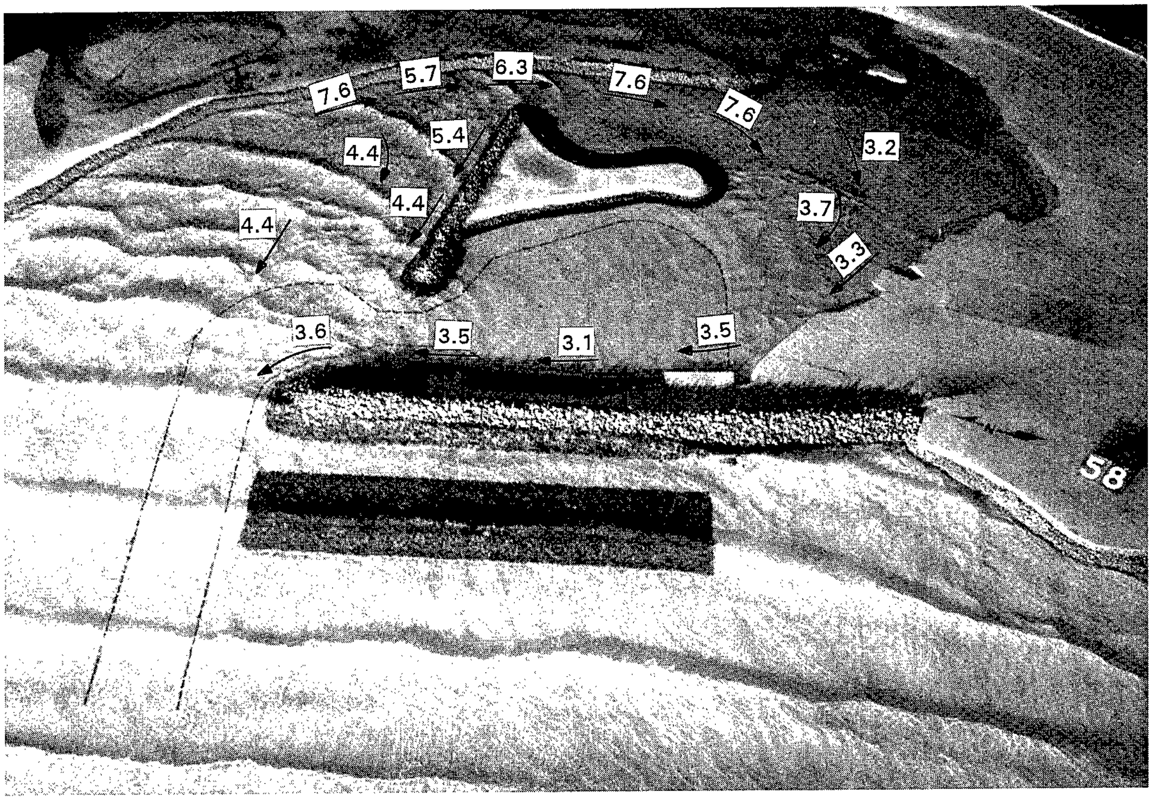


Photo 47. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 11; 12-sec, 16-ft test waves from west; swl = +3.2 ft

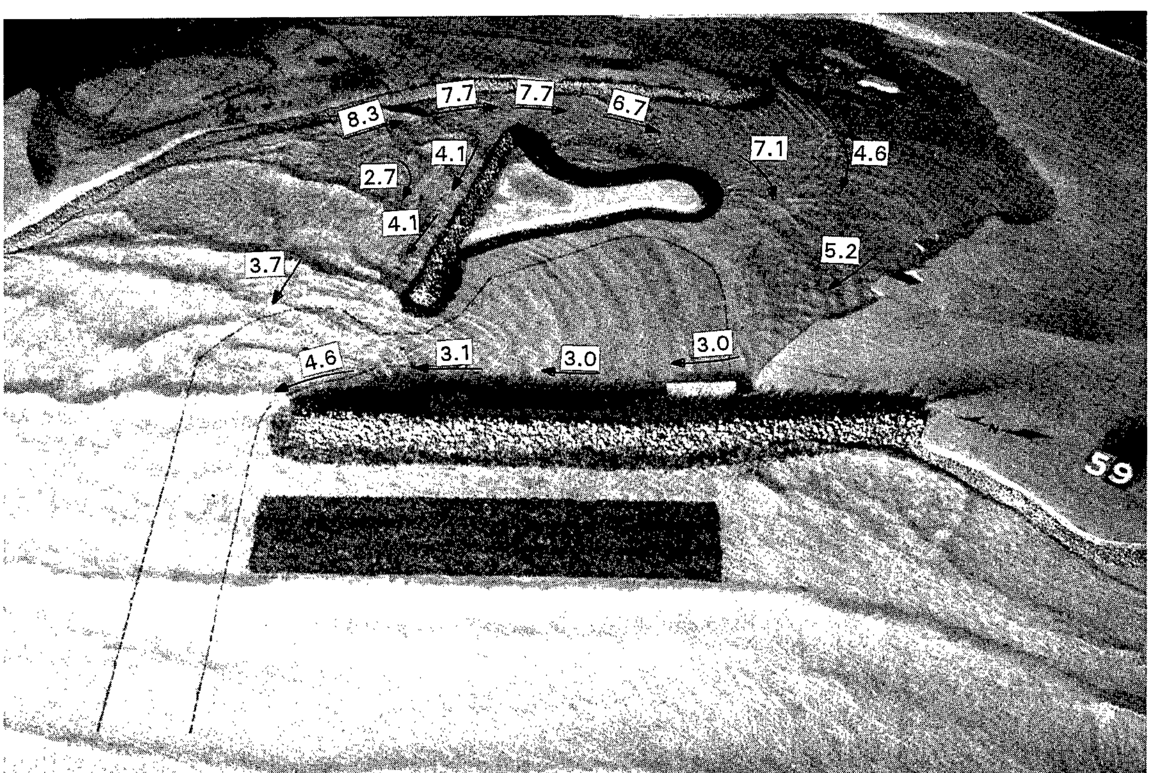


Photo 48. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 11; 16-sec, 19-ft test waves from west; swl = +3.2 ft

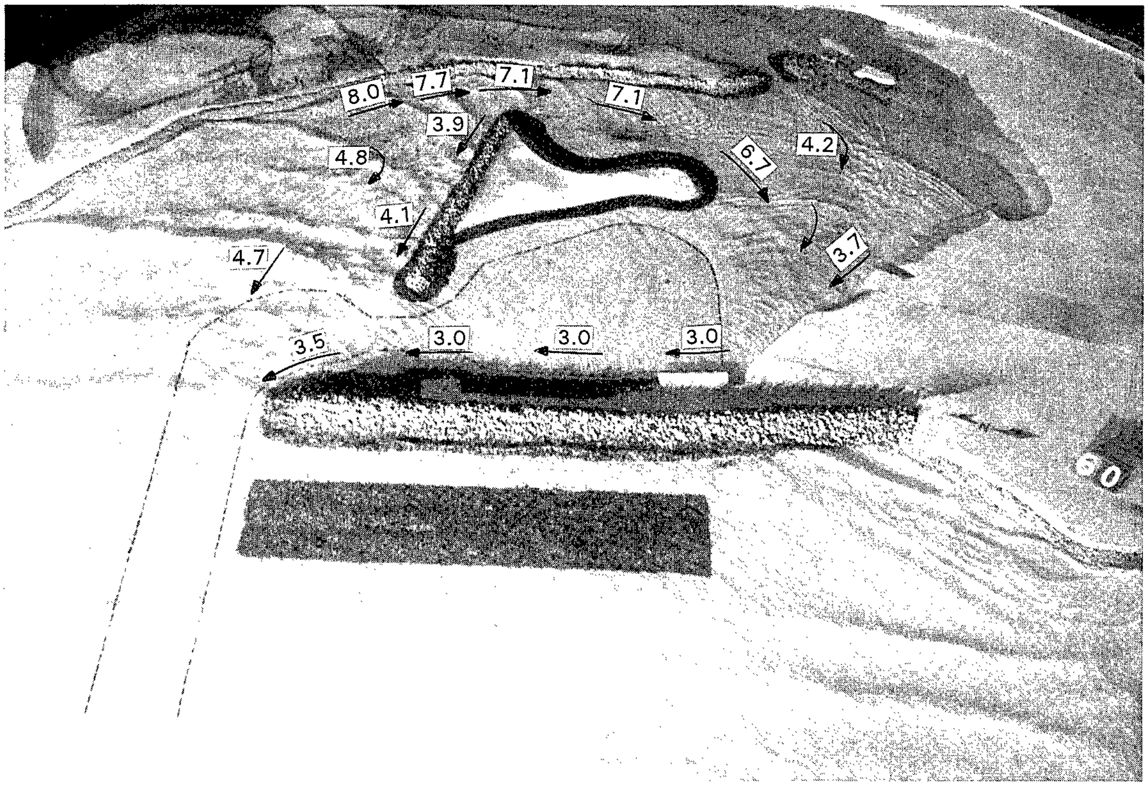


Photo 49. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 11; 20-sec, 14-ft test waves from west; swl = +3.2 ft

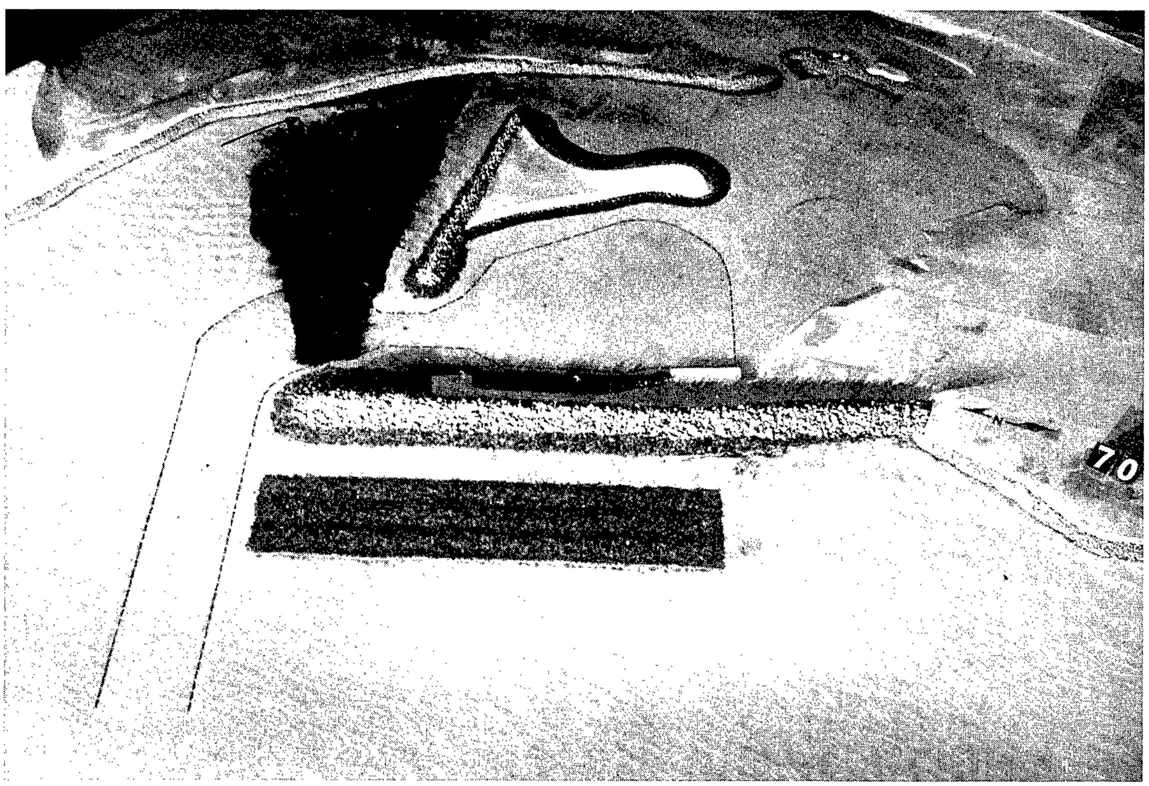


Photo 50. General movement of tracer material and subsequent deposits for Plan 11; 8-sec, 10-ft test waves from west; swl = +3.2 ft (test 1 of a series)

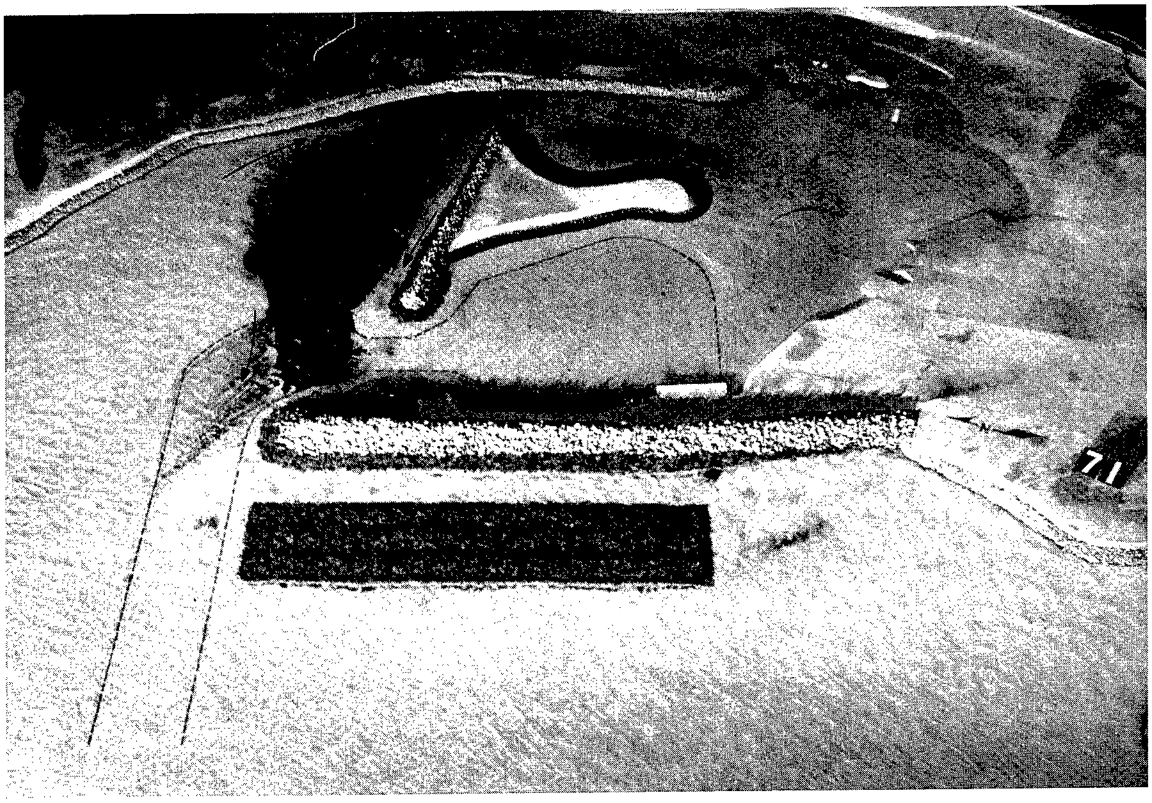


Photo 51. General movement of tracer material and subsequent deposits for Plan 11; 10-sec, 19-ft test waves from west; swl = +3.2 ft (test 2 of a series)

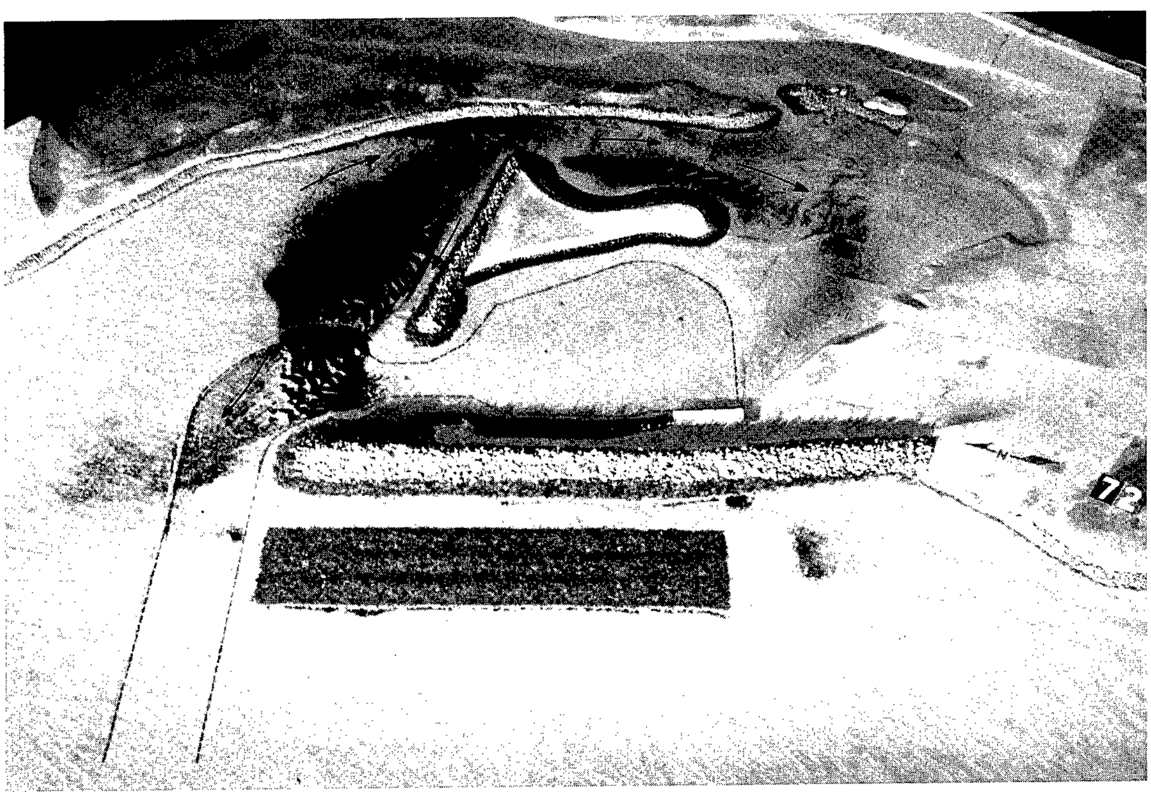


Photo 52. General movement of tracer material and subsequent deposits for Plan 11; 12-sec, 16-ft test waves from west; swl = +3.2 ft (test 3 of a series)

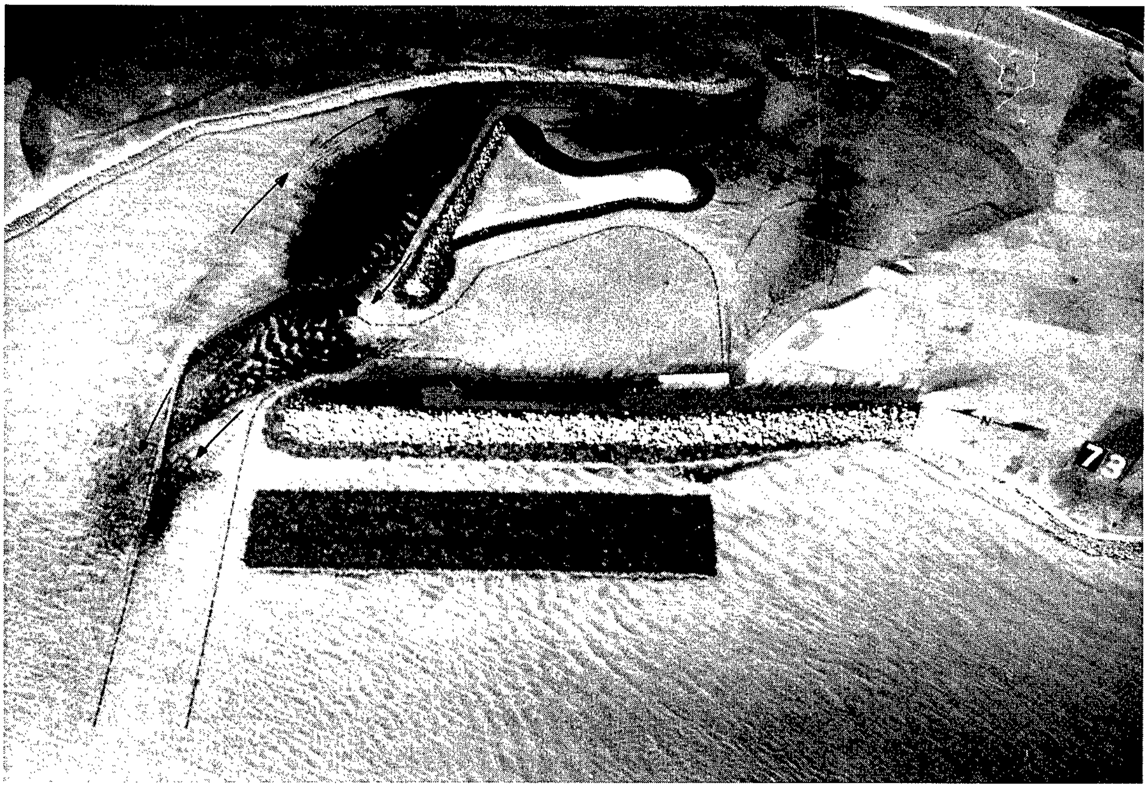


Photo 53. General movement of tracer material and subsequent deposits for Plan 11; 16-sec, 19-ft test waves from west; swl = +3.2 ft (test 4 of a series)

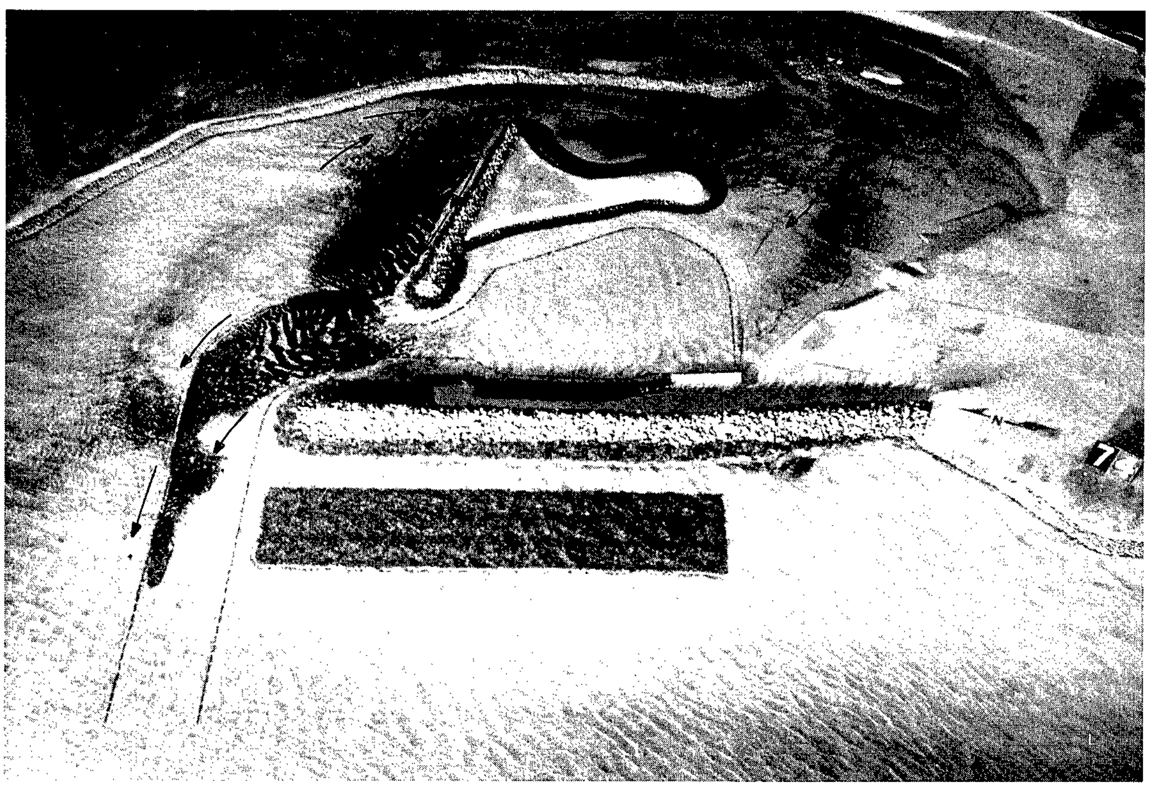


Photo 54. General movement of tracer material and subsequent deposits for Plan 11; 20-sec, 14-ft test waves from west; swl = +3.2 ft (test 5 of a series)

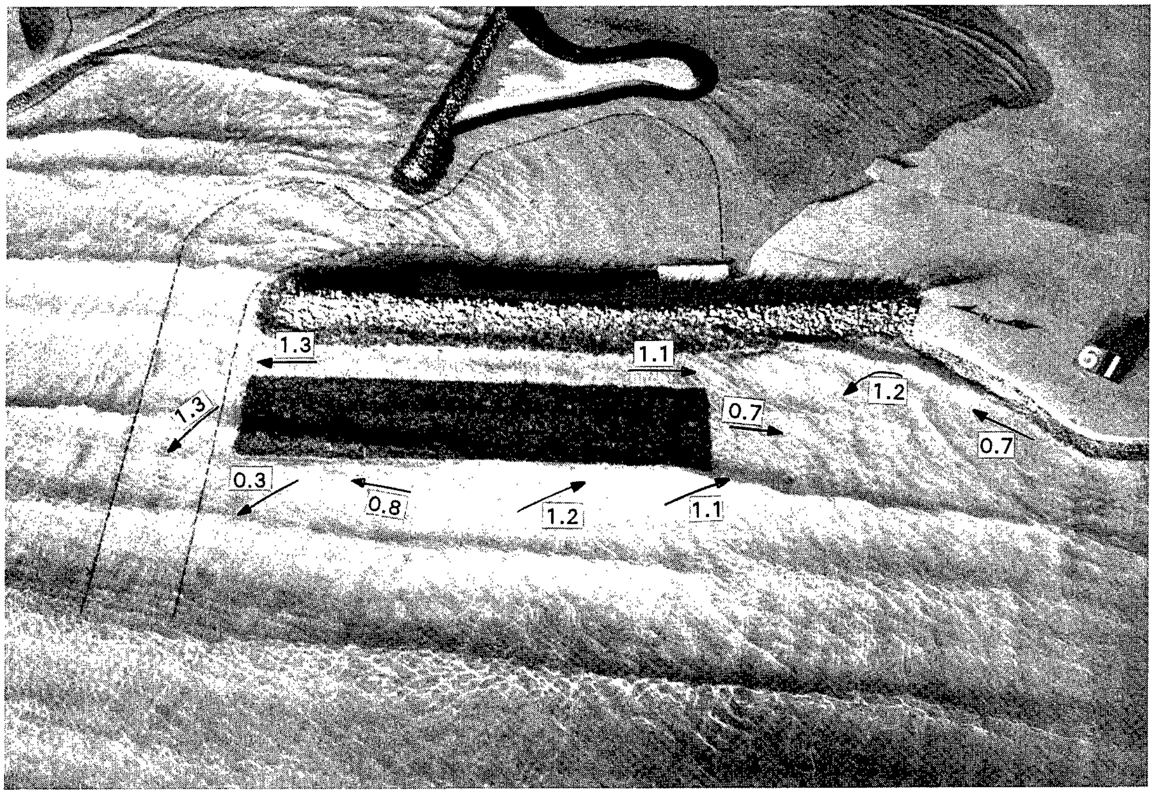


Photo 55. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 11; 16-sec, 14.4-ft test wave from west; swl = +7.0 ft

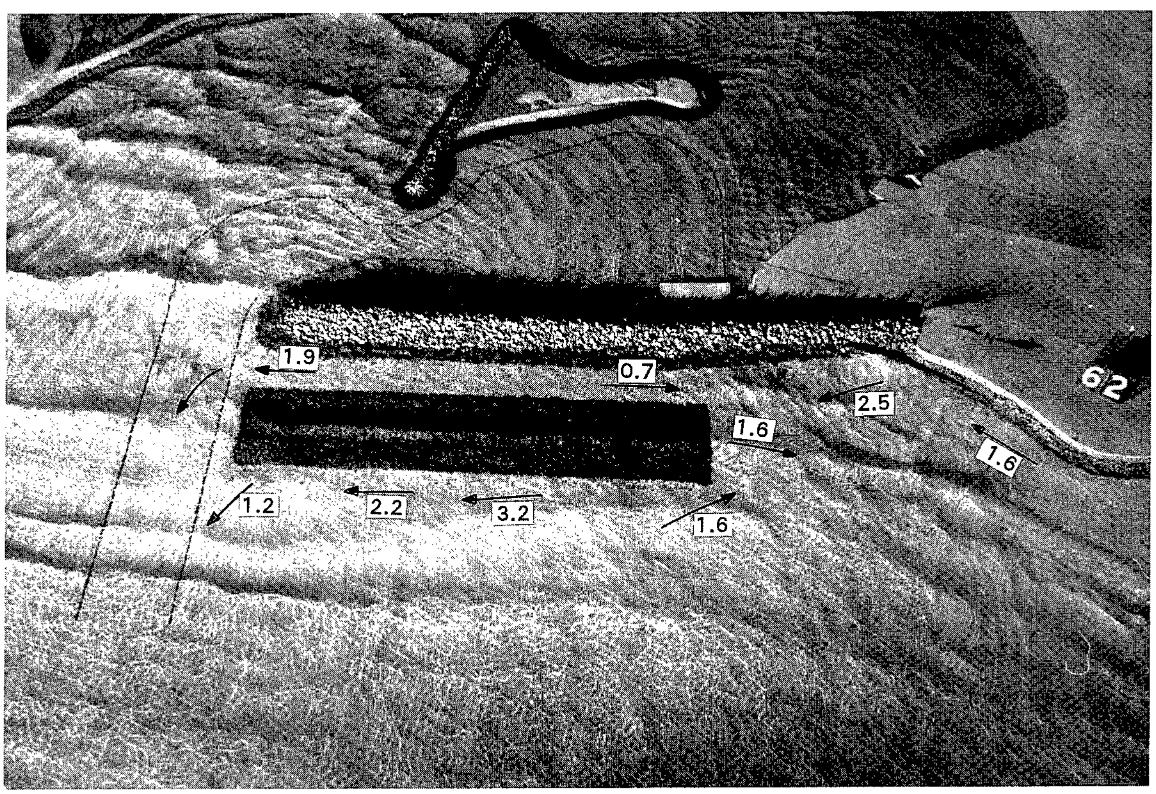


Photo 56. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 11; 16-sec, 19-ft test waves from west; swl = +7.0 ft

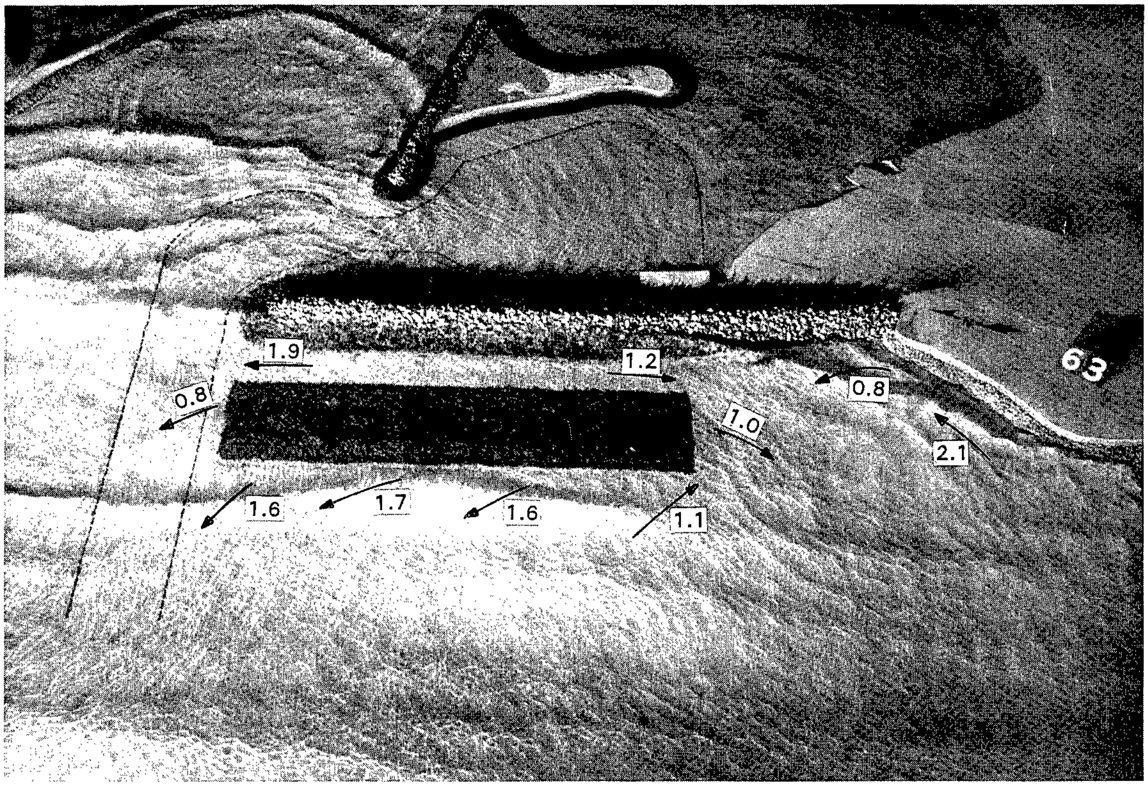


Photo 57. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 11; 20-sec, 14-ft test waves from west; swl = +7.0 ft

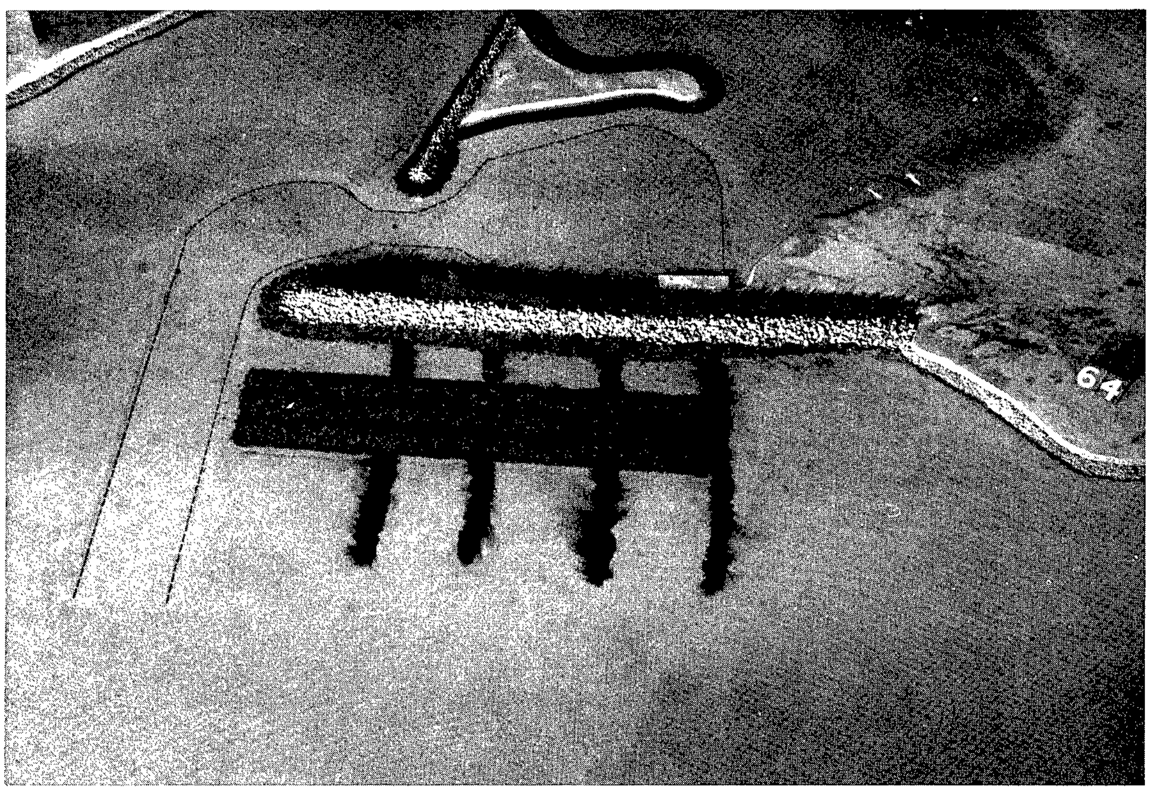


Photo 58. Placement of tracer material seaward of main breakwater for Plan 11 prior to model testing

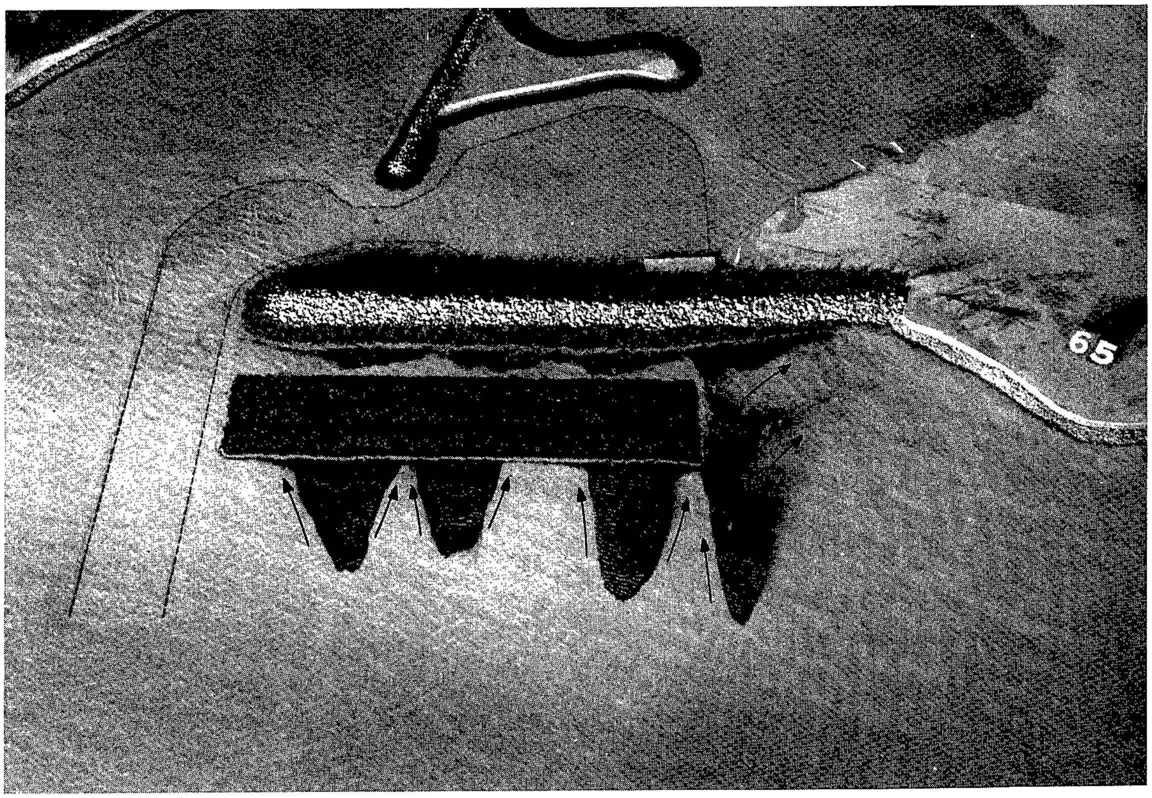


Photo 59. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 11; 16-sec, 14.4-ft test waves from west; swl = +7.0 ft

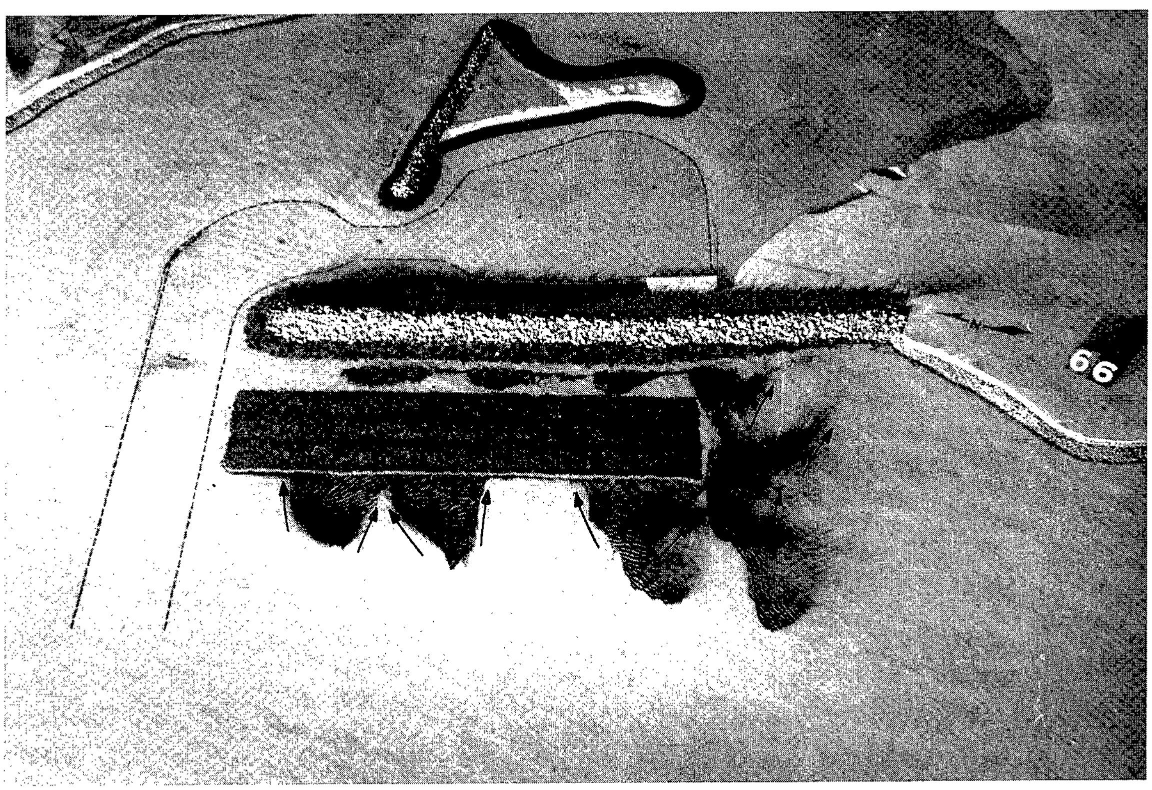


Photo 60. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 11; 16-sec, 19-ft test waves from west; swl = +7.0 ft

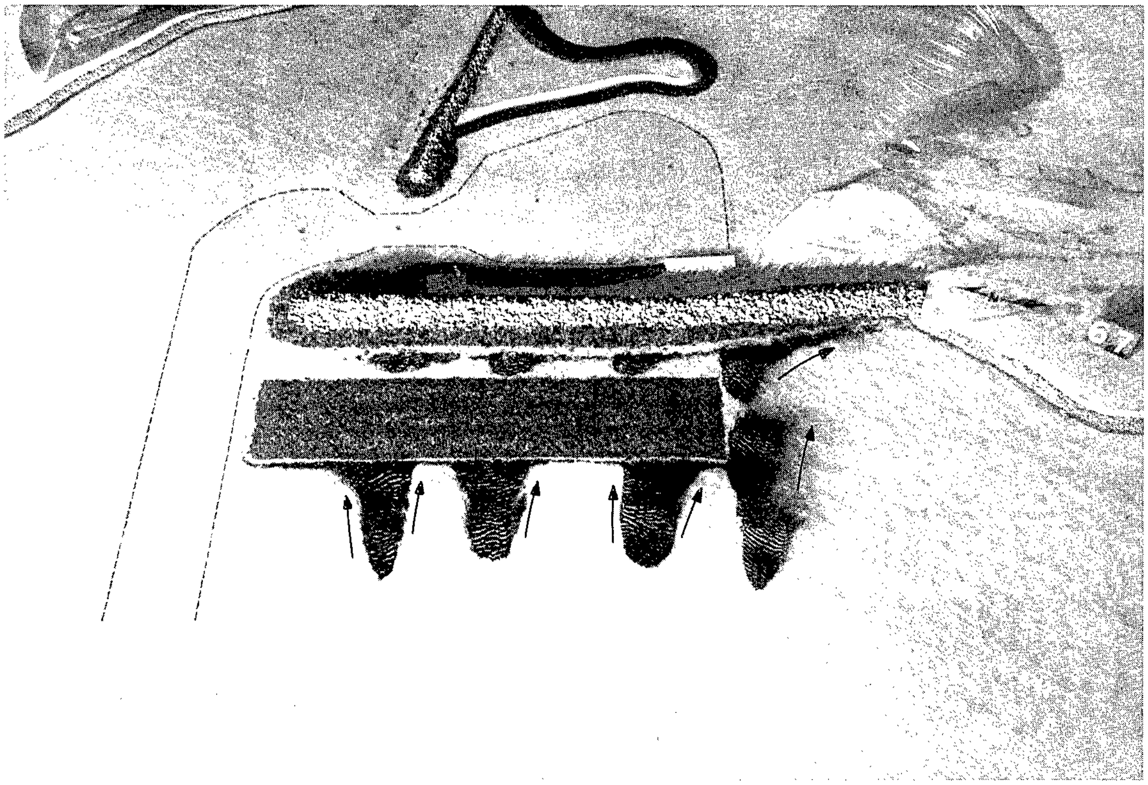


Photo 61. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 11; 20-sec, 14-ft test waves from west; swl = +7.0 ft

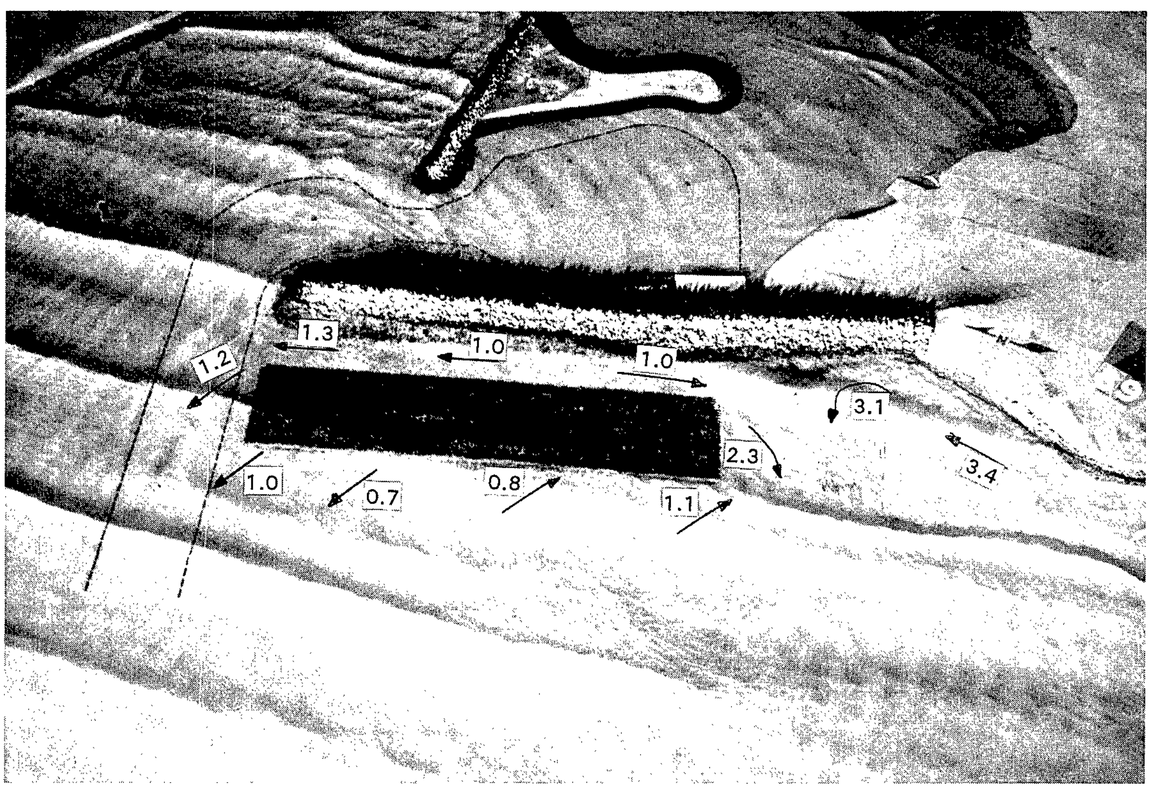


Photo 62. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 11; 16-sec, 14.4-ft test waves from west-northwest; swl = +7.0 ft

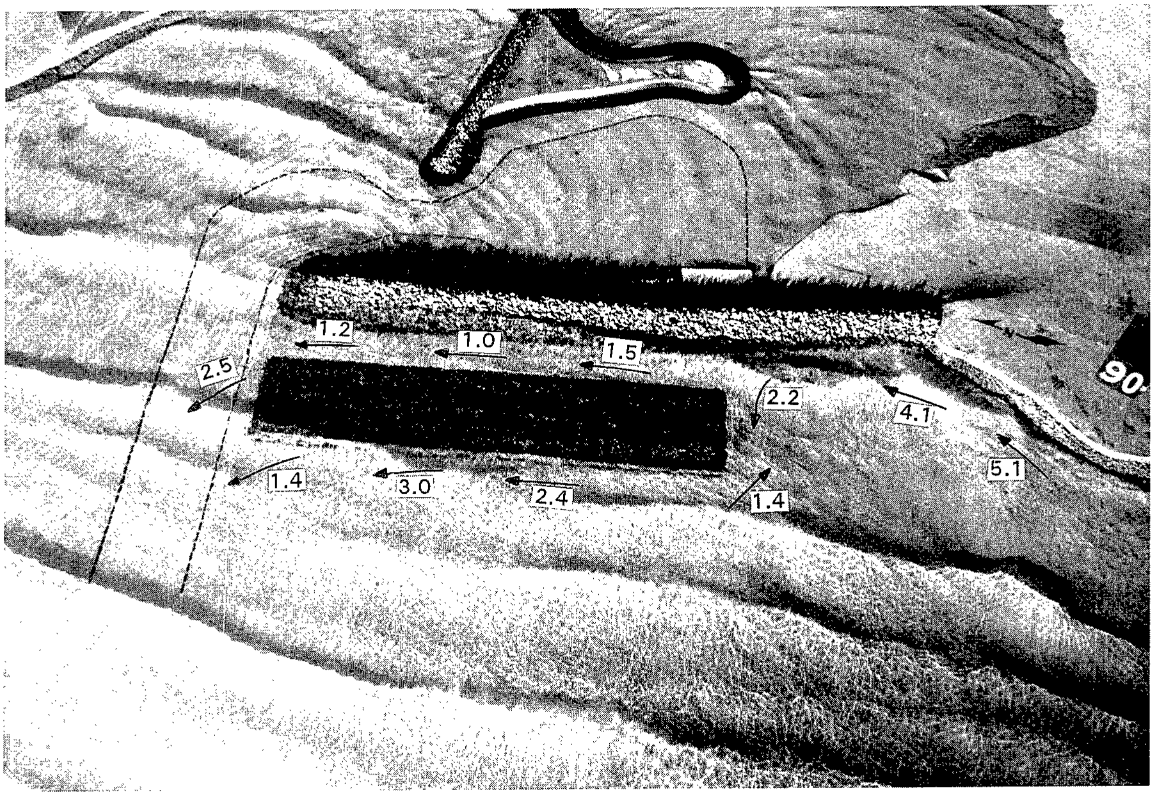


Photo 63. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 11; 16-sec, 19-ft test waves from west-northwest; swl = +7.0 ft

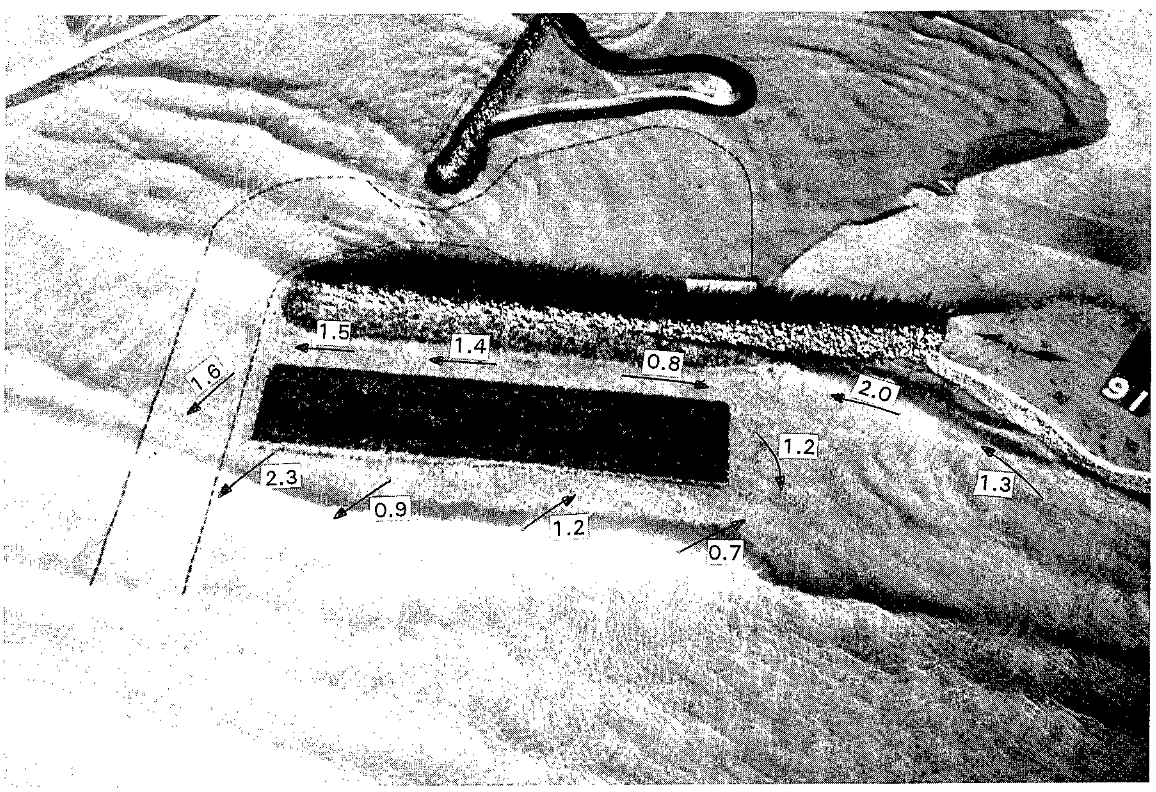


Photo 64. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) seaward of main breakwater for Plan 11, 20-sec, 14-ft test waves from west-northwest; swl = +7.0 ft

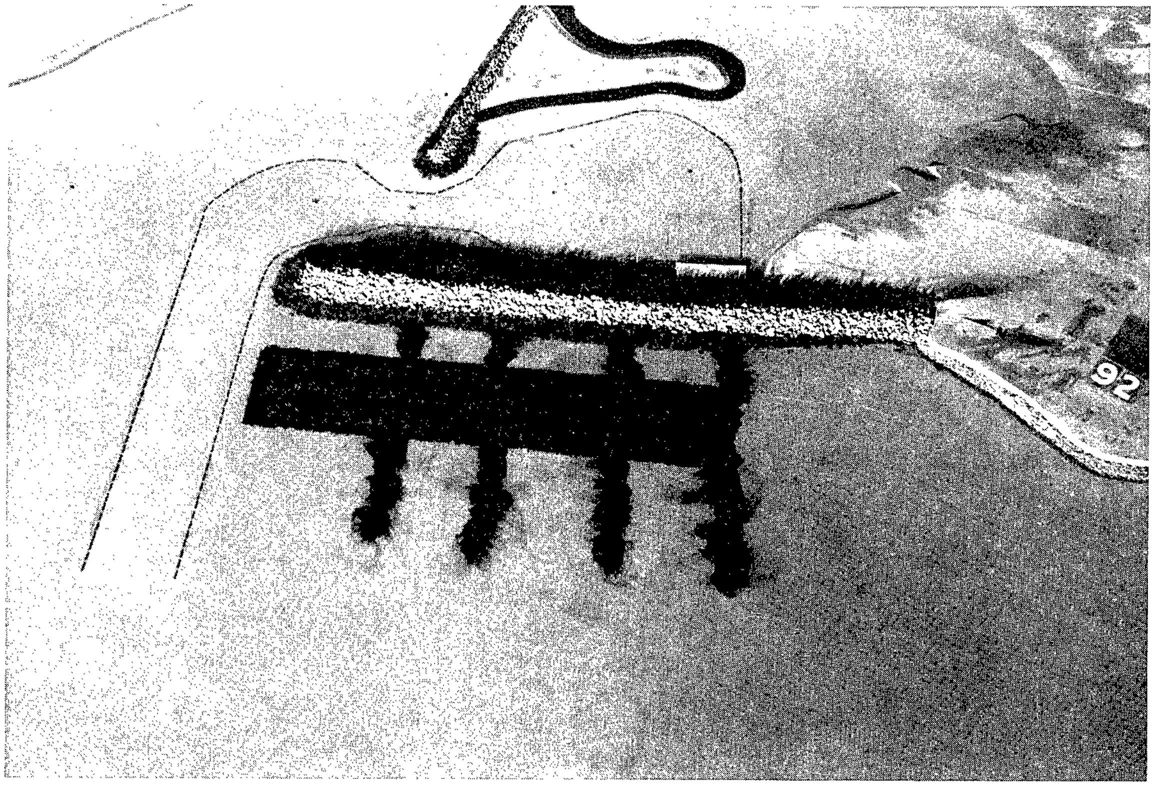


Photo 65. Placement of tracer material seaward of main breakwater for Plan 11 prior to model testing for waves from west-northwest

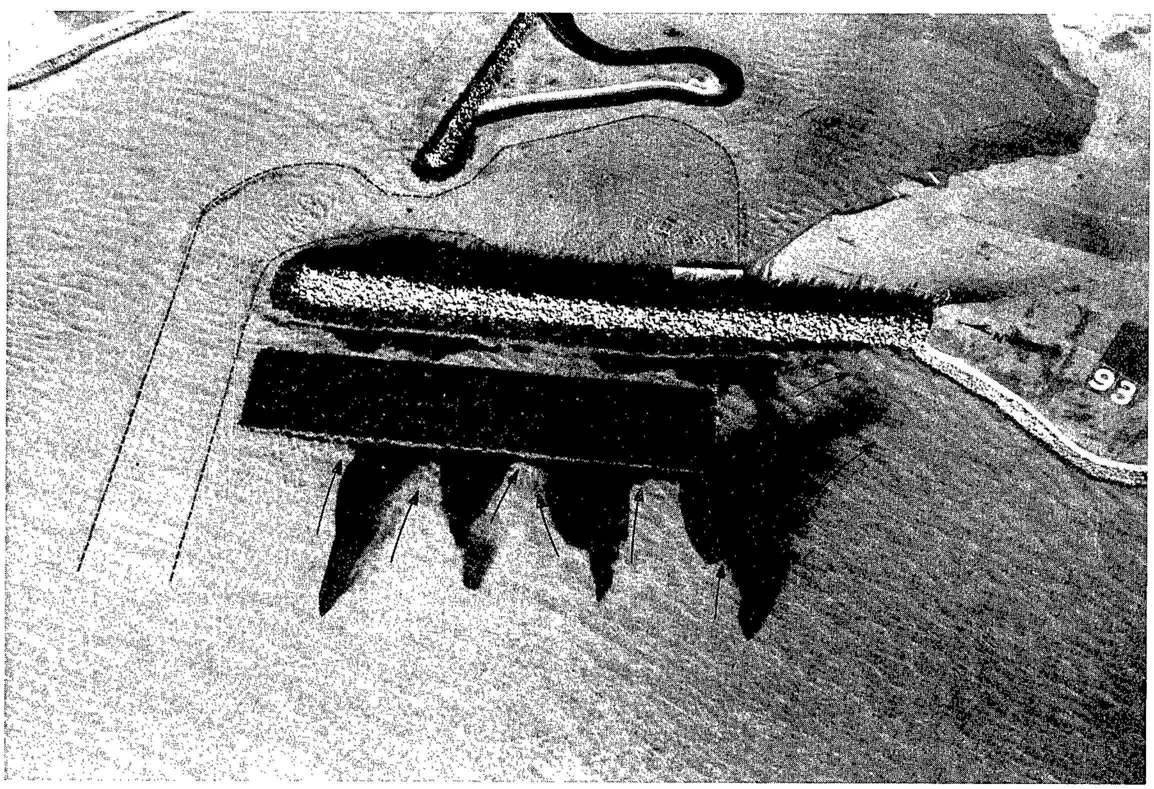


Photo 66. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 11; 16-sec, 14.4-ft test waves from west-northwest; swl = +7.0 ft

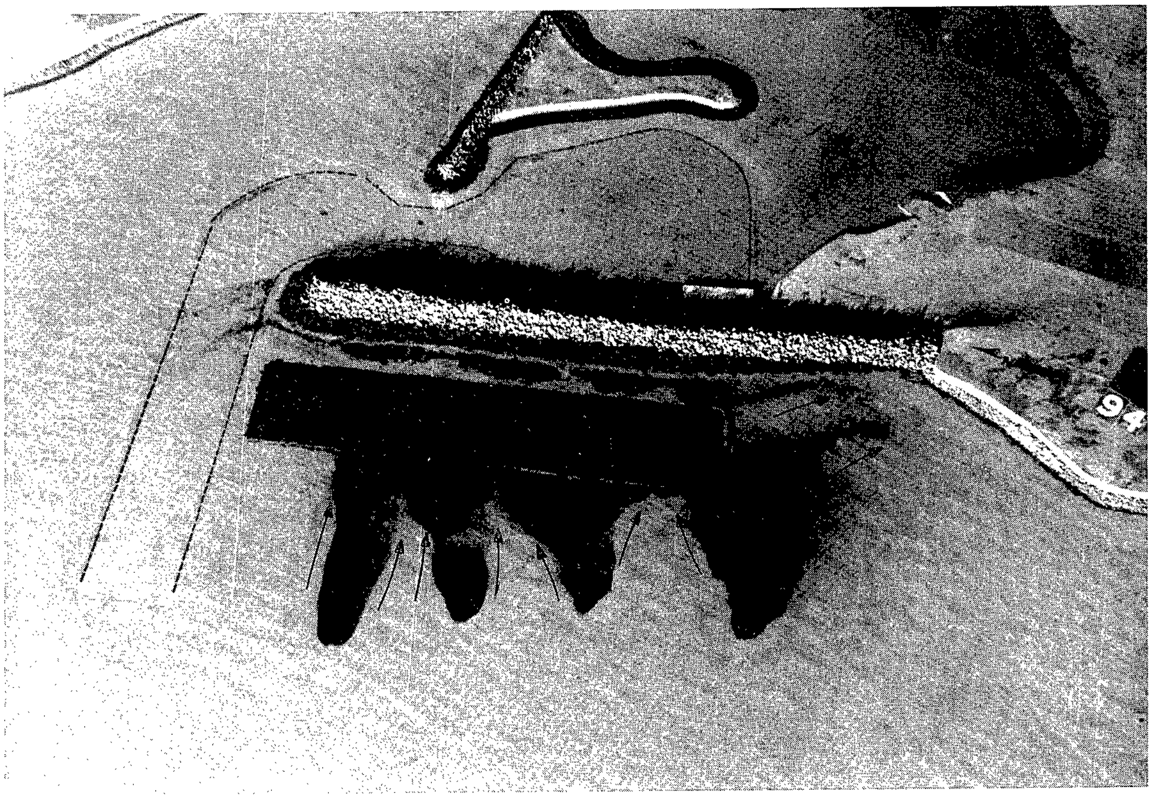


Photo 67. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 11; 16-sec, 19-ft test waves from west-northwest; swl = +7.0 ft

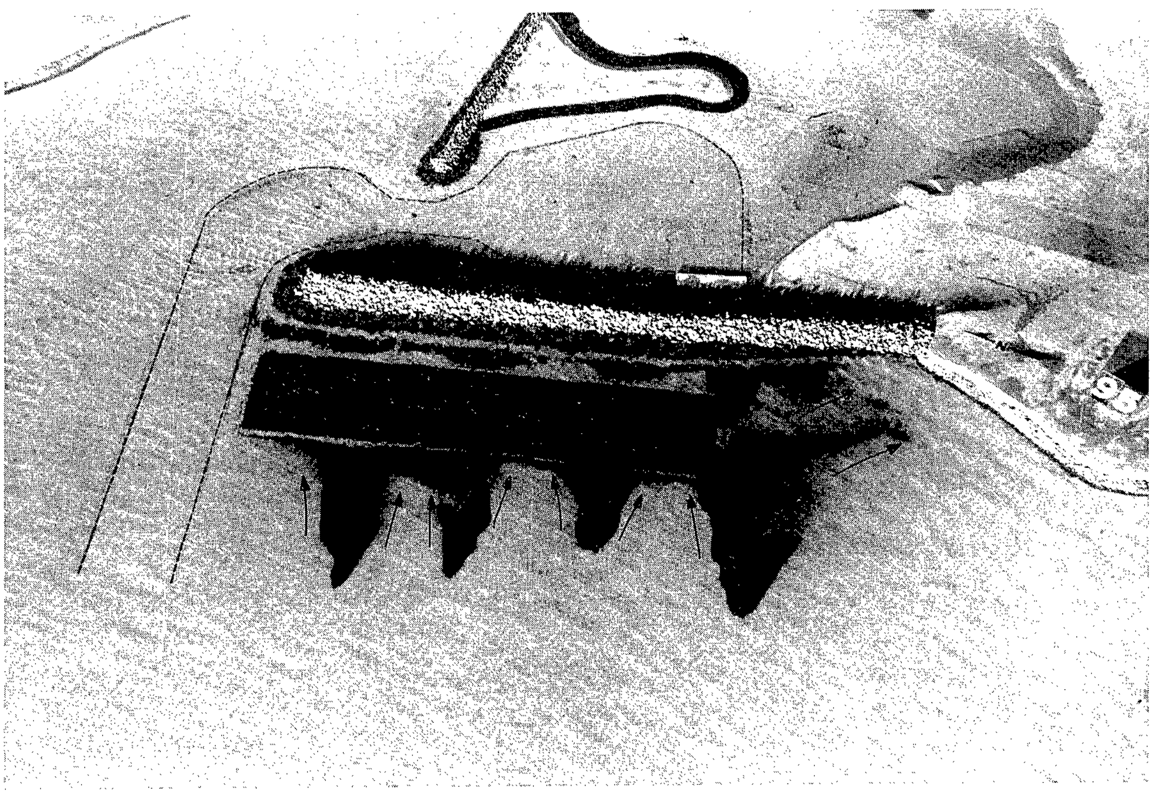


Photo 68. General movement of tracer material and subsequent deposits seaward of the main breakwater for Plan 11; 20-sec, 14-ft test waves from west-northwest; swl = +7.0 ft

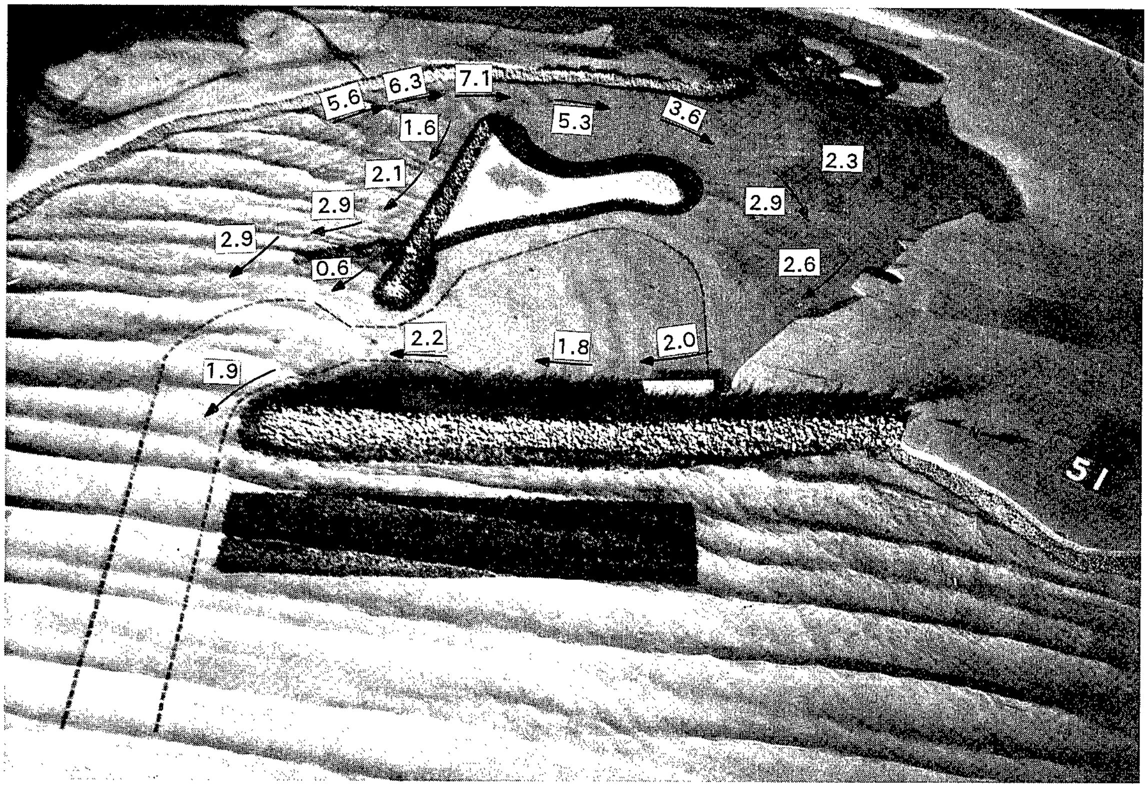


Photo 69. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 12; 8-sec, 10-ft test waves from west; swl = +3.2 ft

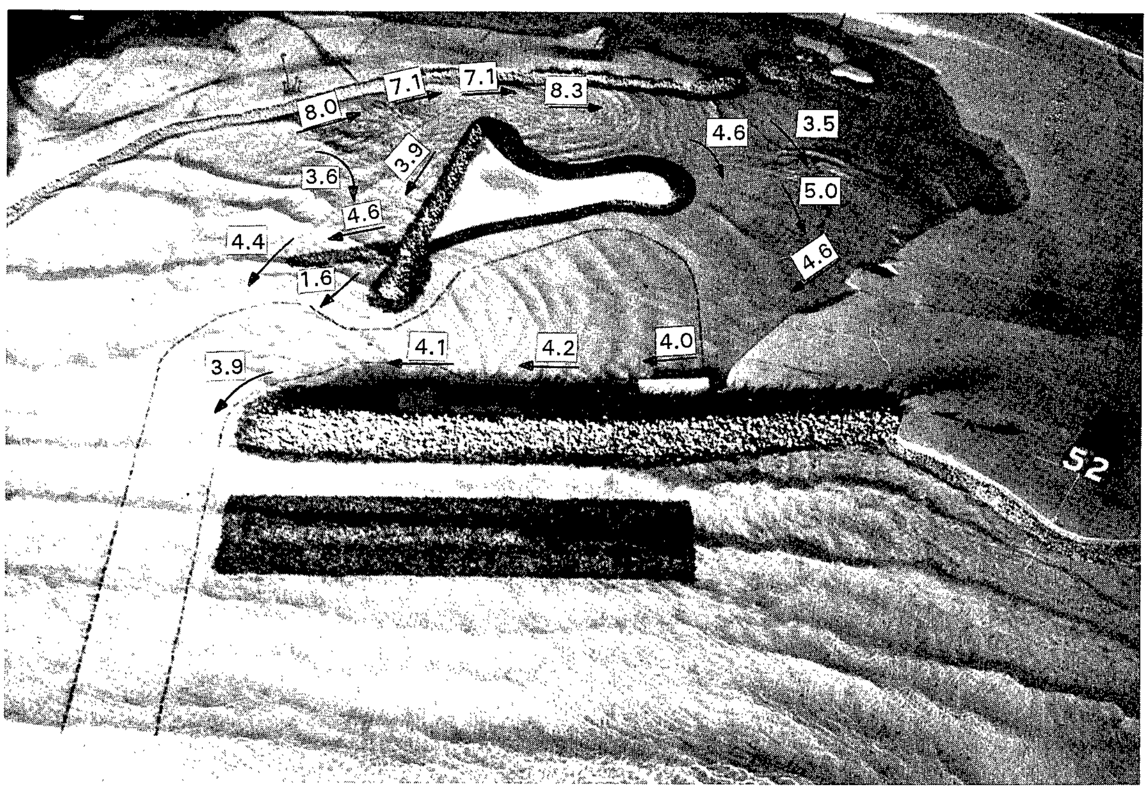


Photo 70. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 12; 12-sec, 16-ft test waves from west; swl = +3.2 ft

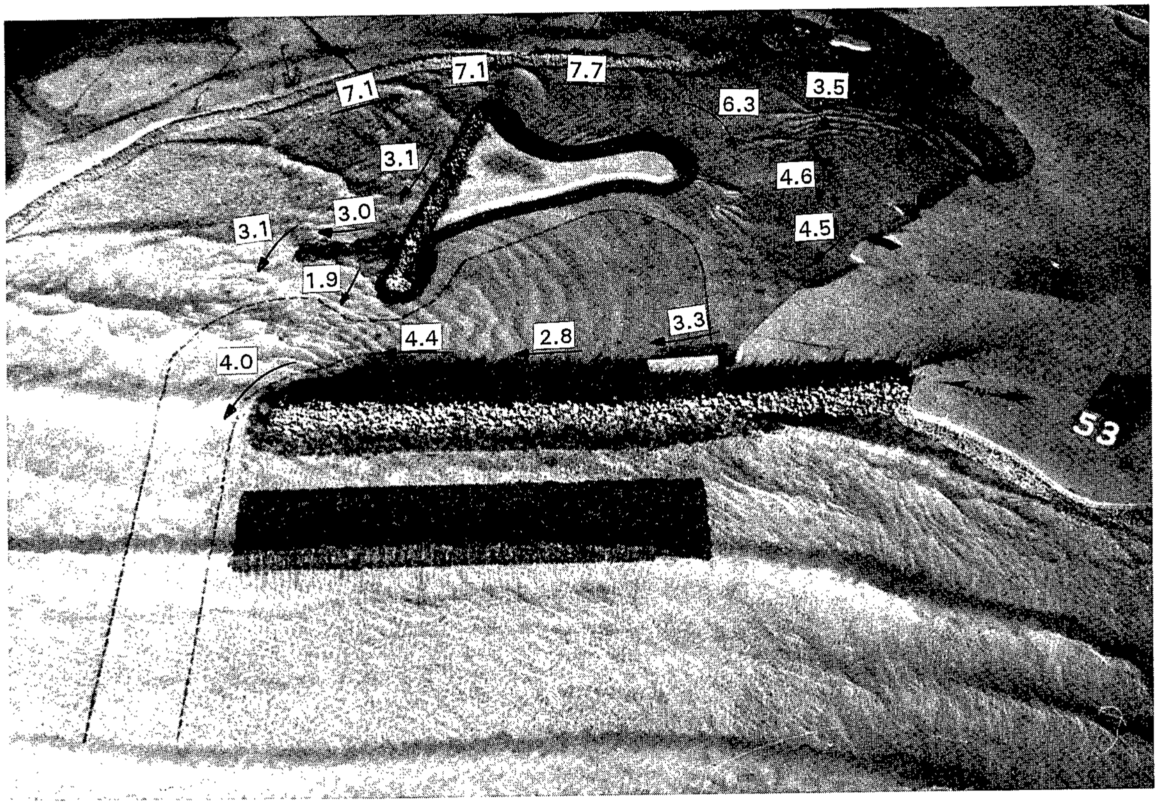


Photo 71. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 12; 16-sec, 19-ft test waves from west; swl = +3.2 ft

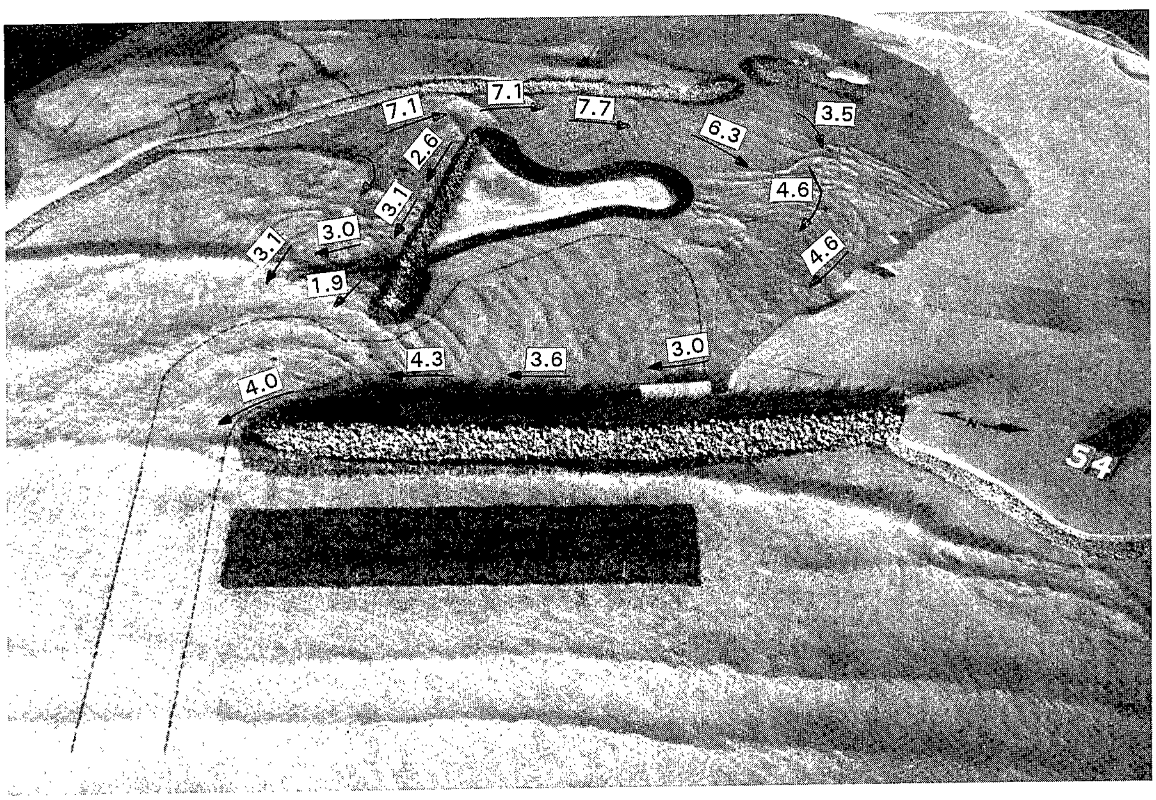


Photo 72. Typical wave patterns, current patterns, and current magnitudes (prototype feet per second) for Plan 12; 20-sec, 14-ft test waves from west; swl = +3.2 ft

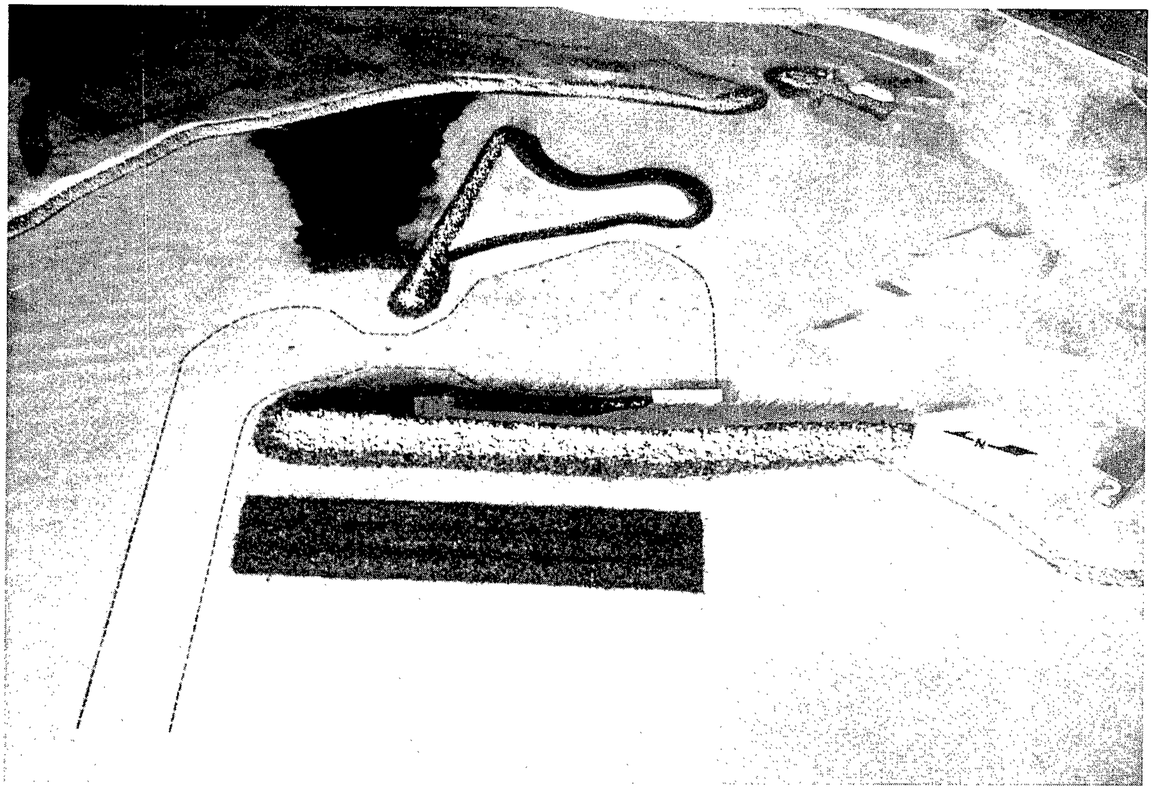


Photo 73. Placement of tracer material for Plan 12 prior to model testing

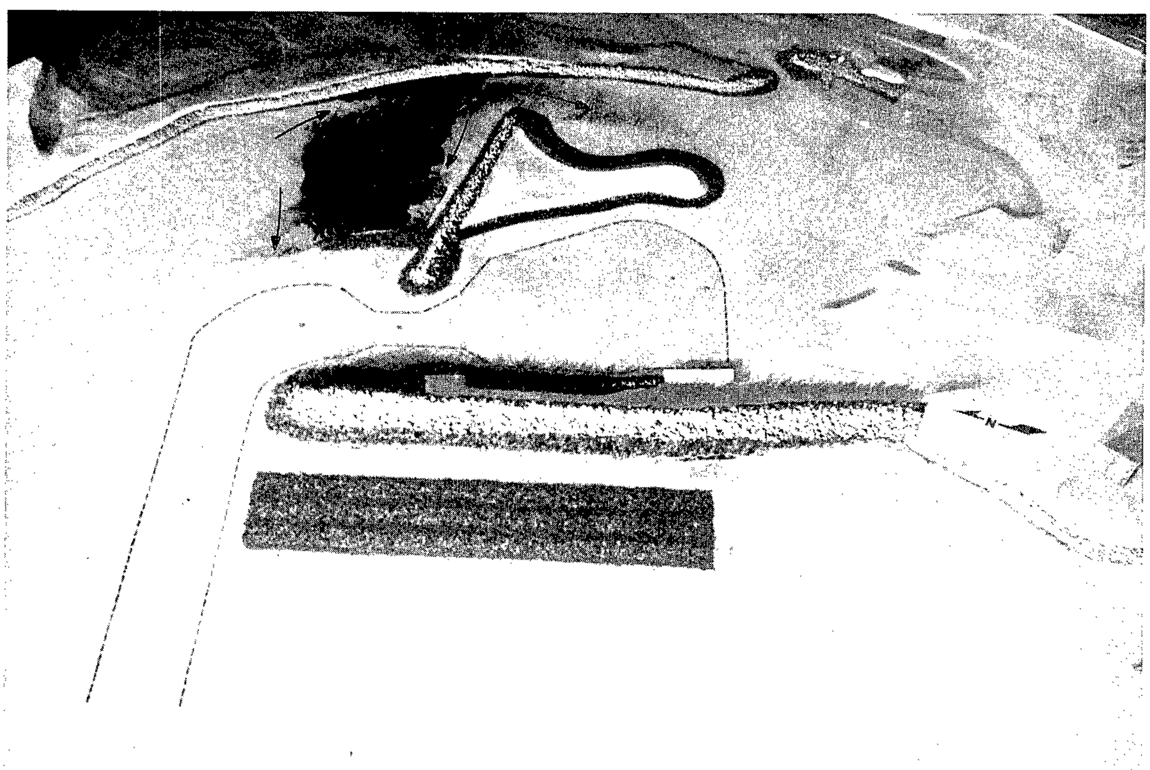


Photo 74. General movement of tracer material and subsequent deposits for Plan 12; 8-sec, 10-ft test waves from west; swl = +3.2 ft (test 1 of a series)

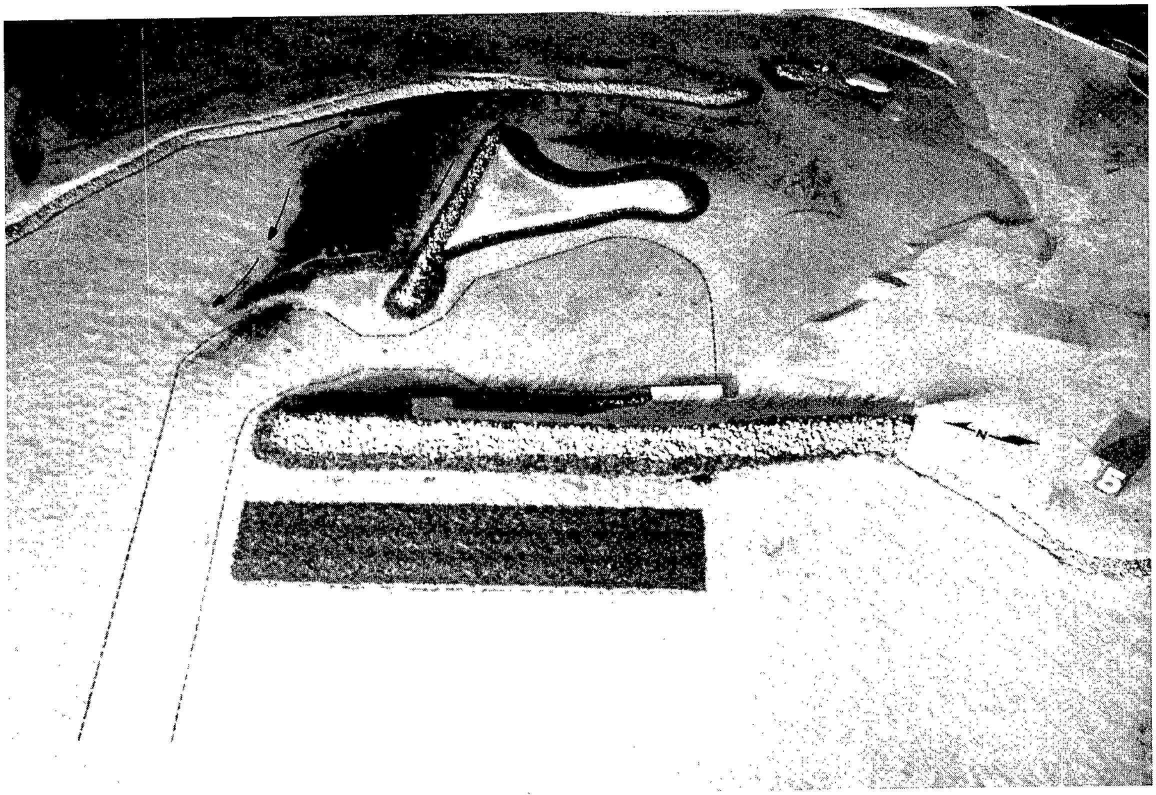


Photo 75. General movement of tracer material and subsequent deposits for Plan 12; 10-sec, 19-ft test waves from west; swl = +3.2 ft (test 2 of a series)

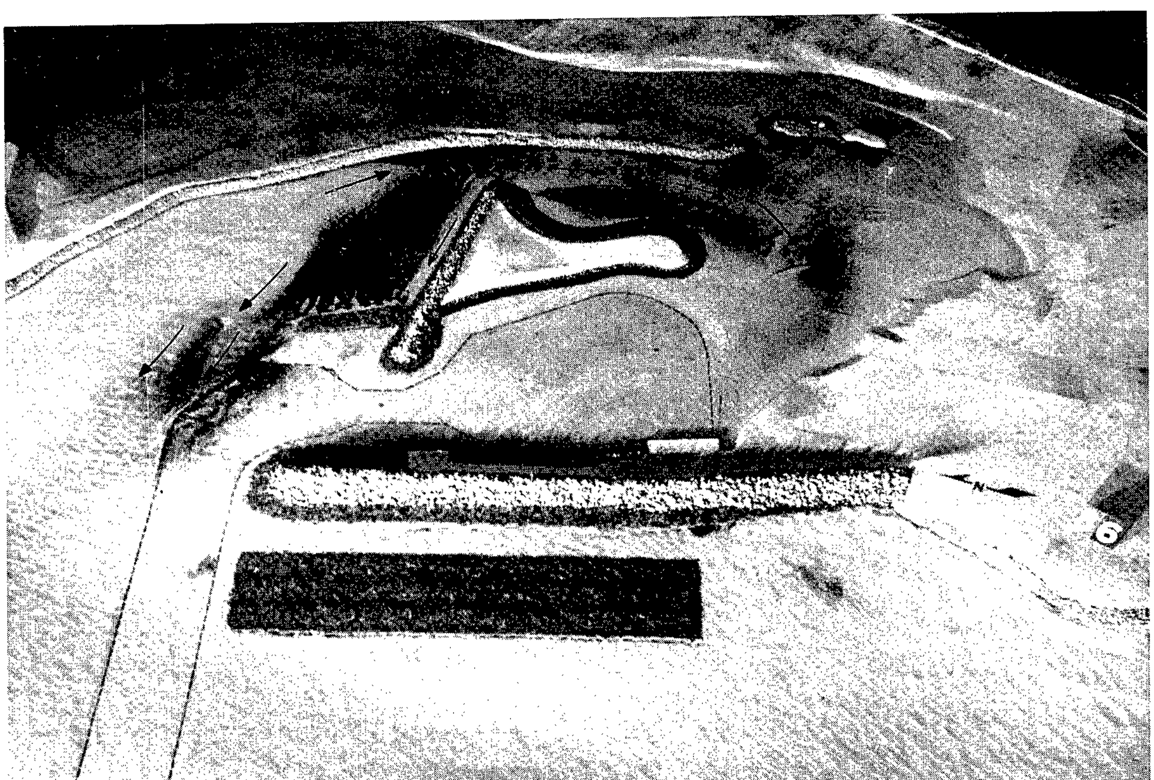


Photo 76. General movement of tracer material and subsequent deposits for Plan 12; 12-sec, 16-ft test waves from west; swl = +3.2 ft (test 3 of a series)

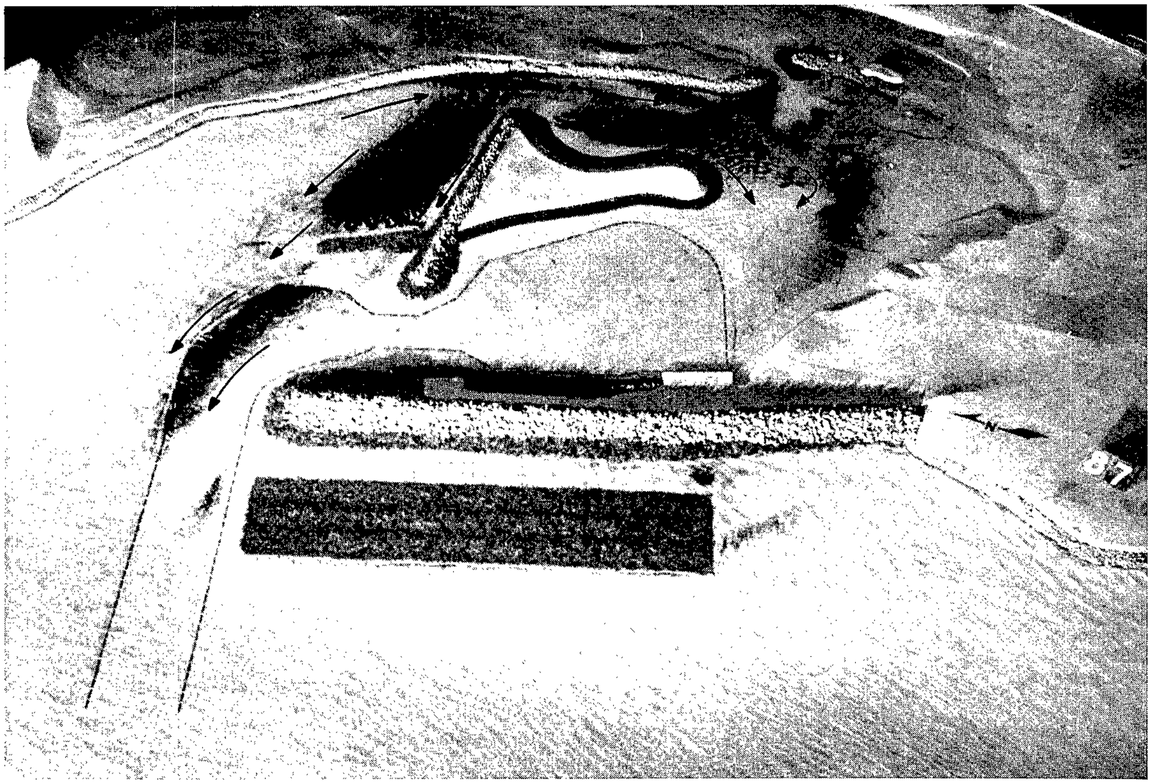


Photo 77. General movement of tracer material and subsequent deposits for Plan 12; 16-sec, 19-ft test waves from west; swl = +3.2 ft (test 4 of a series)

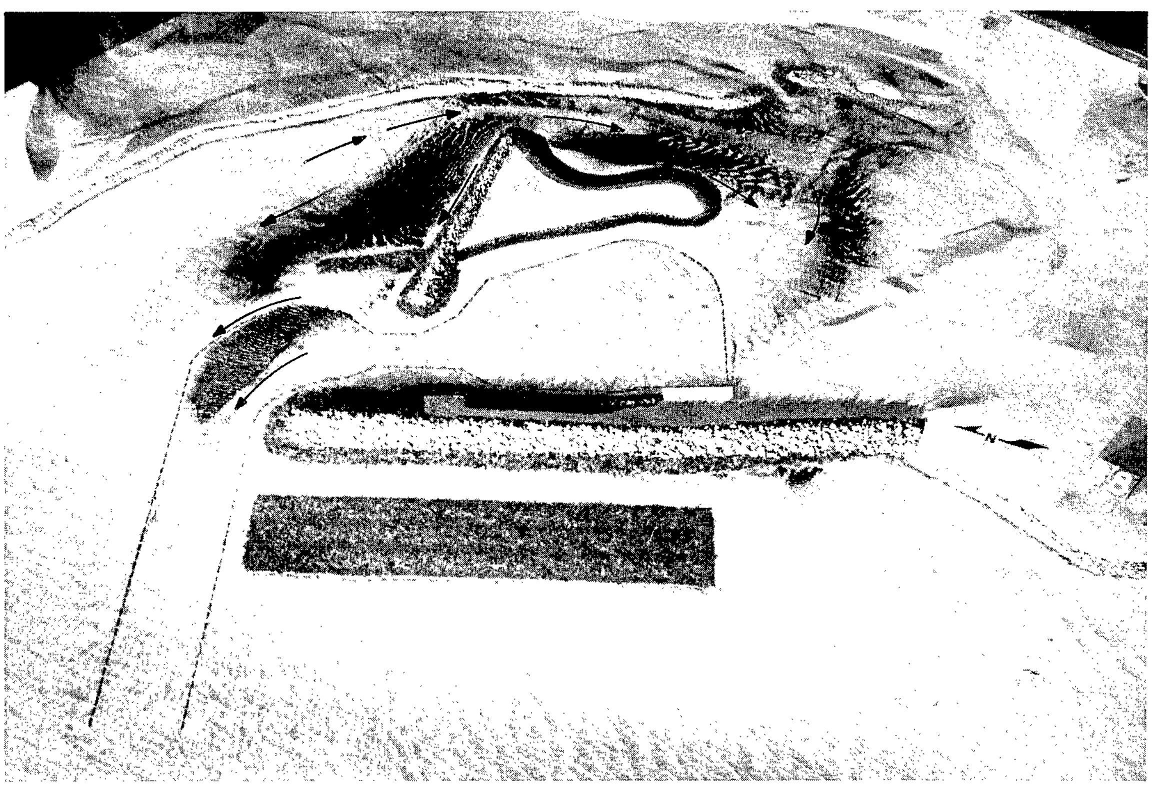
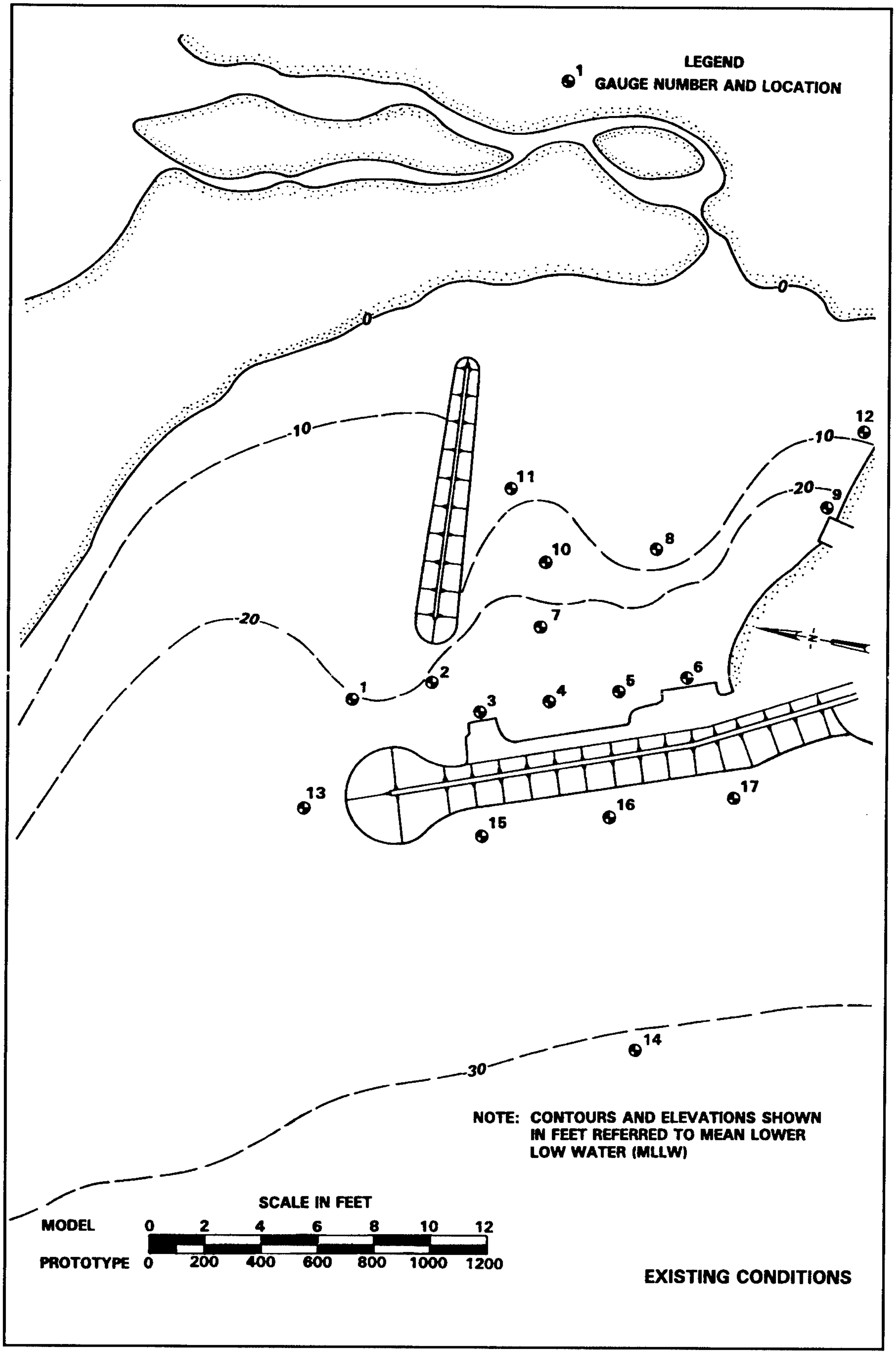
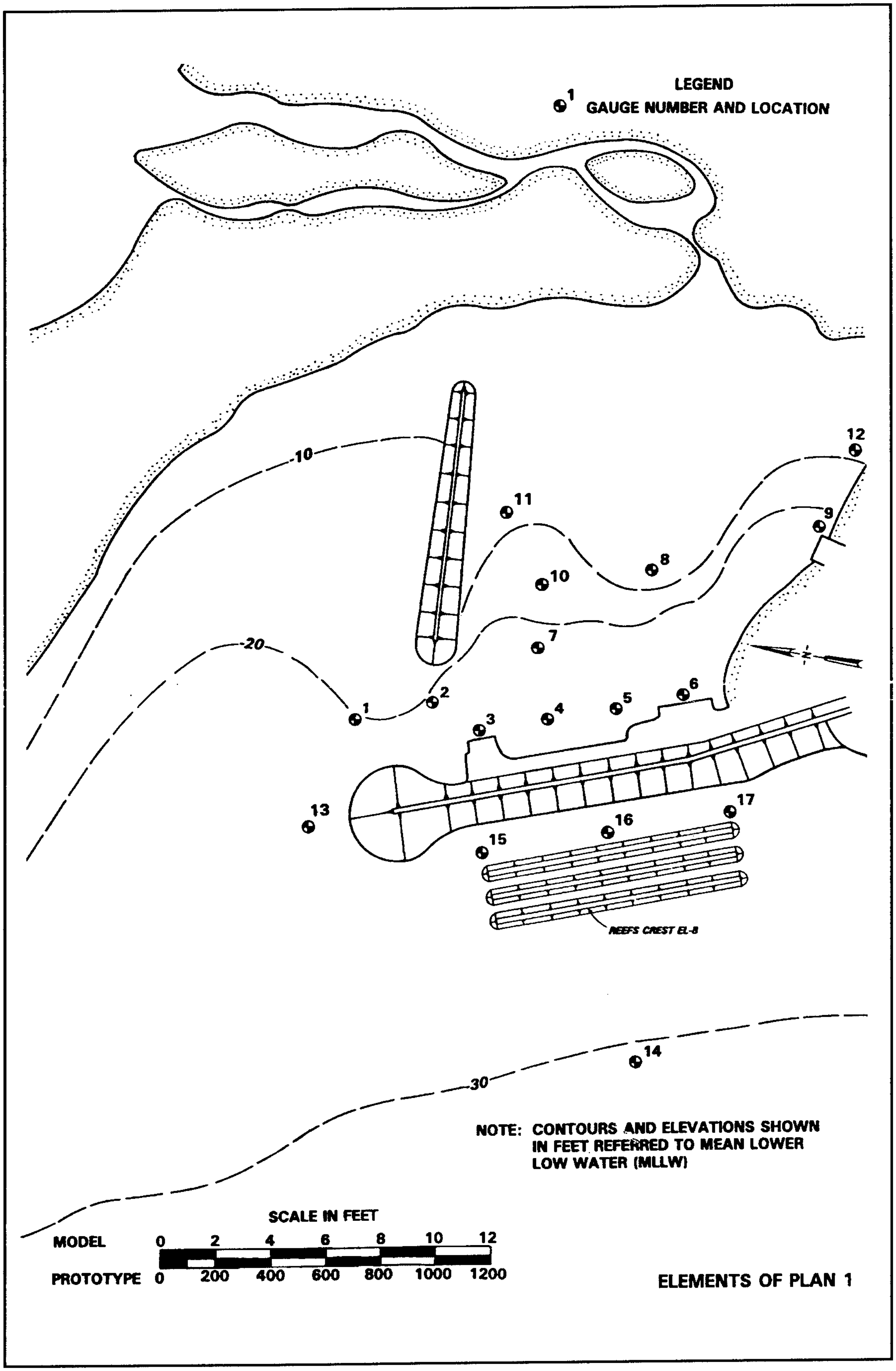
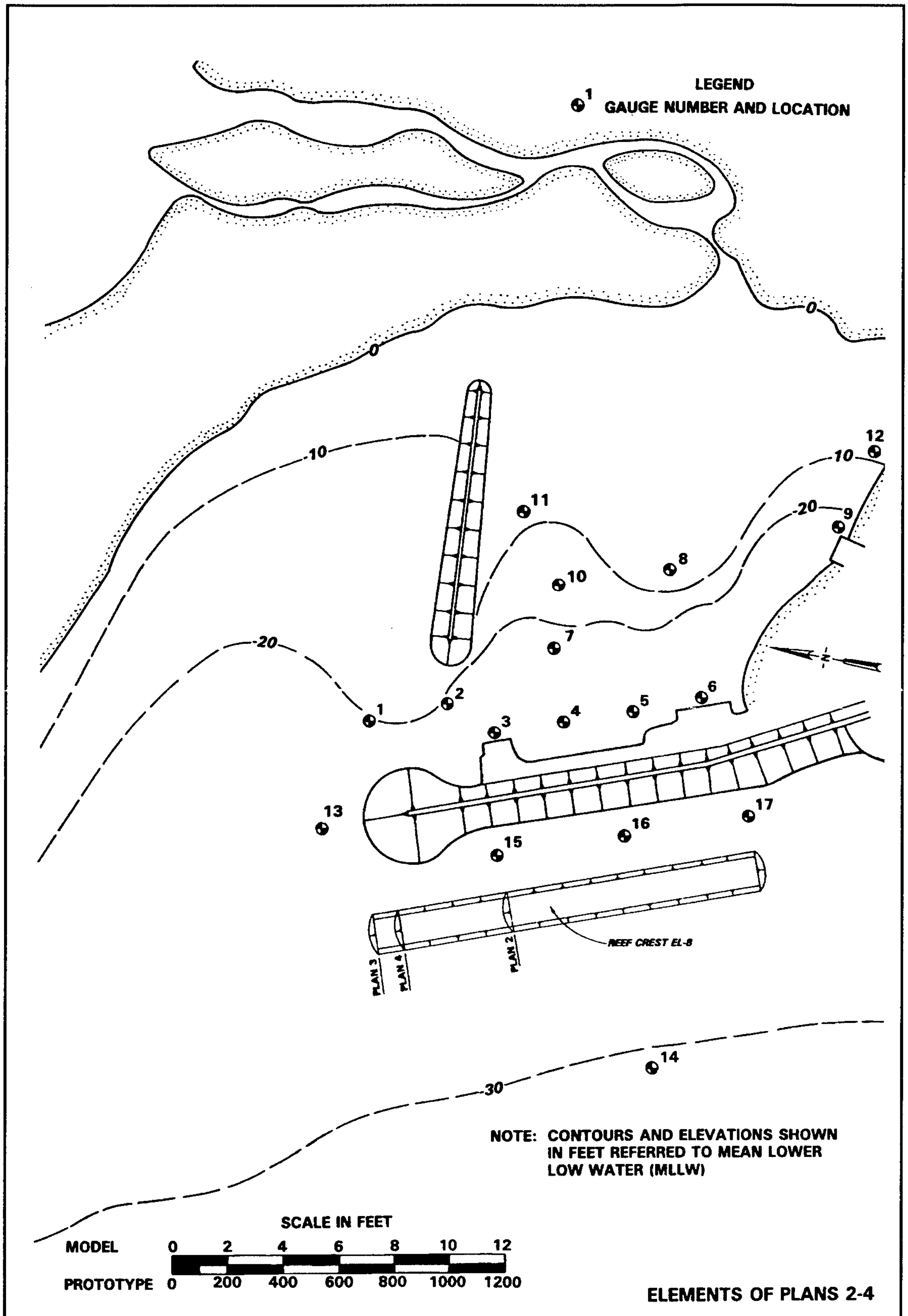


Photo 78. General movement of tracer material and subsequent deposits for Plan 12; 20-sec, 14-ft test waves from west; swl = +3.2 ft (test 5 of a series)

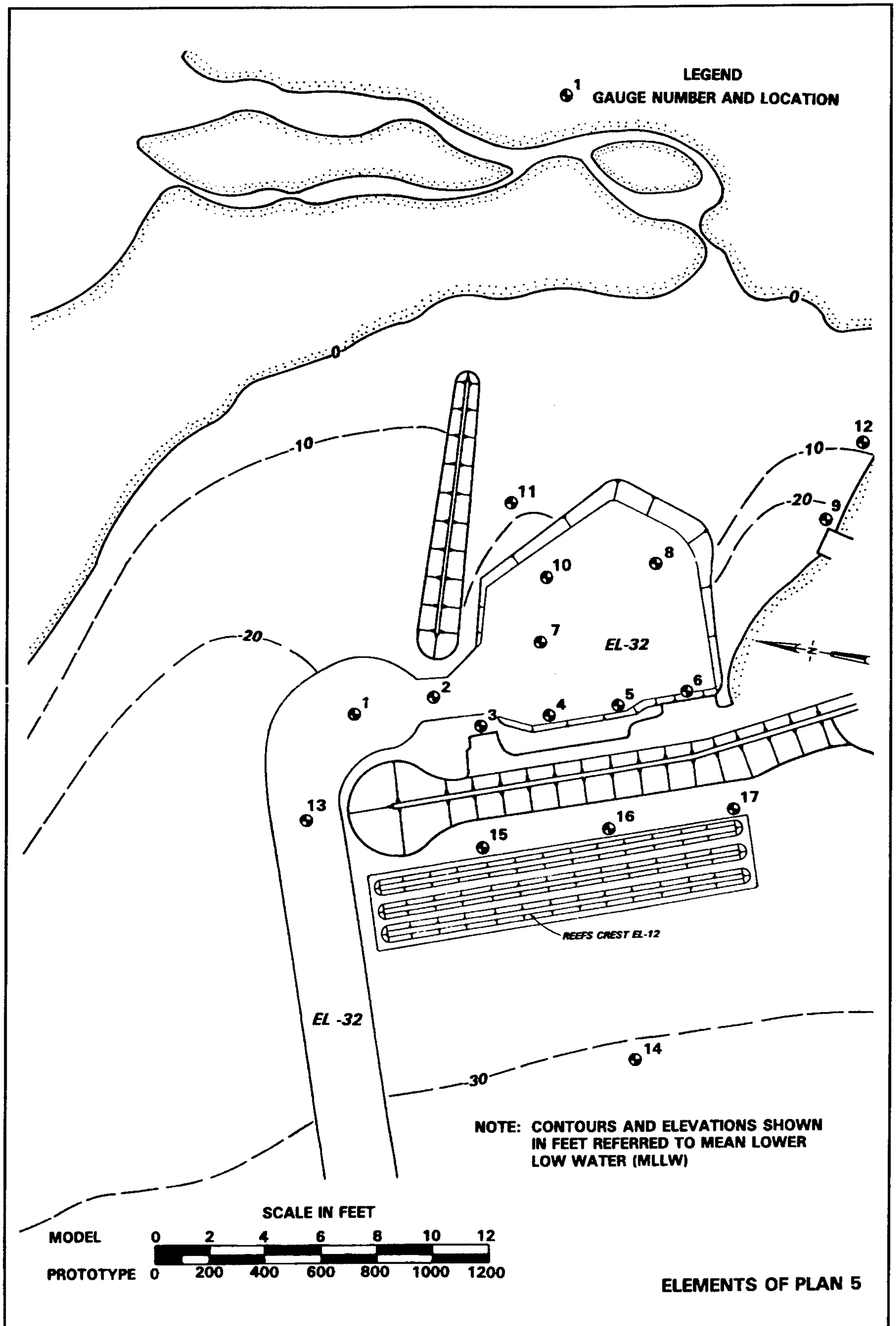


LEGEND
1
GAUGE NUMBER AND LOCATION
0
0
10
10
20
20
30
12
11
10
9
8
7
6
5
4
3
2
1
13
15
16
17
14
NOTE: CONTOURS AND ELEVATIONS SHOWN IN FEET REFERRED TO MEAN LOWER LOW WATER (MLLW)
SCALE IN FEET
MODEL 0 2 4 6 8 10 12
PROTOTYPE 0 200 400 600 800 1000 1200
EXISTING CONDITIONS

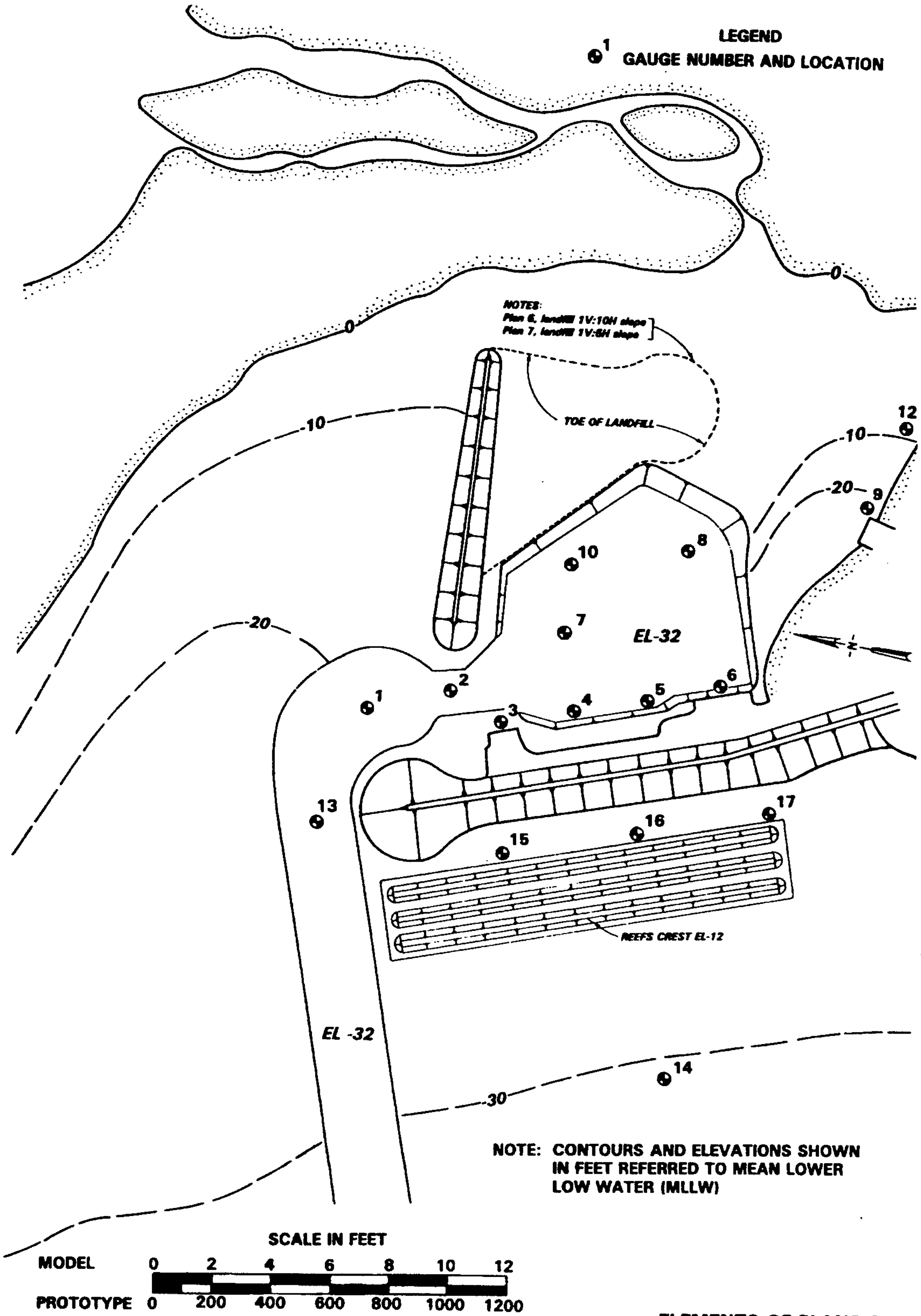

LEGEND
1 GAUGE NUMBER AND LOCATION
10
20
30
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
N
REEFS CREST EL-8
NOTE: CONTOURS AND ELEVATIONS SHOWN IN FEET REFERRED TO MEAN LOWER LOW WATER (MLLW)
SCALE IN FEET
MODEL 0 2 4 6 8 10 12
PROTOTYPE 0 200 400 600 800 1000 1200
ELEMENTS OF PLAN 1



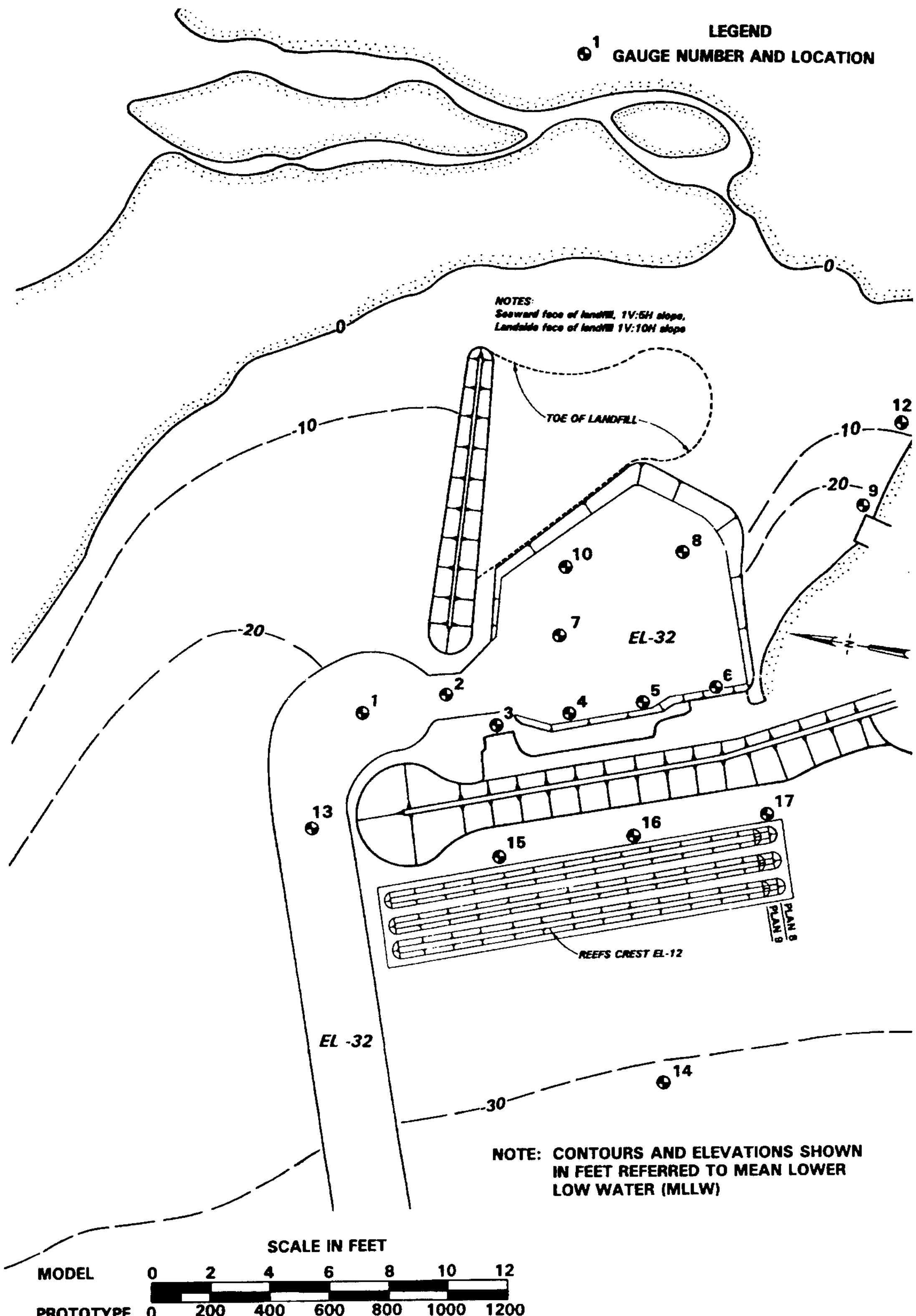
ELEMENTS OF PLANS 2-4



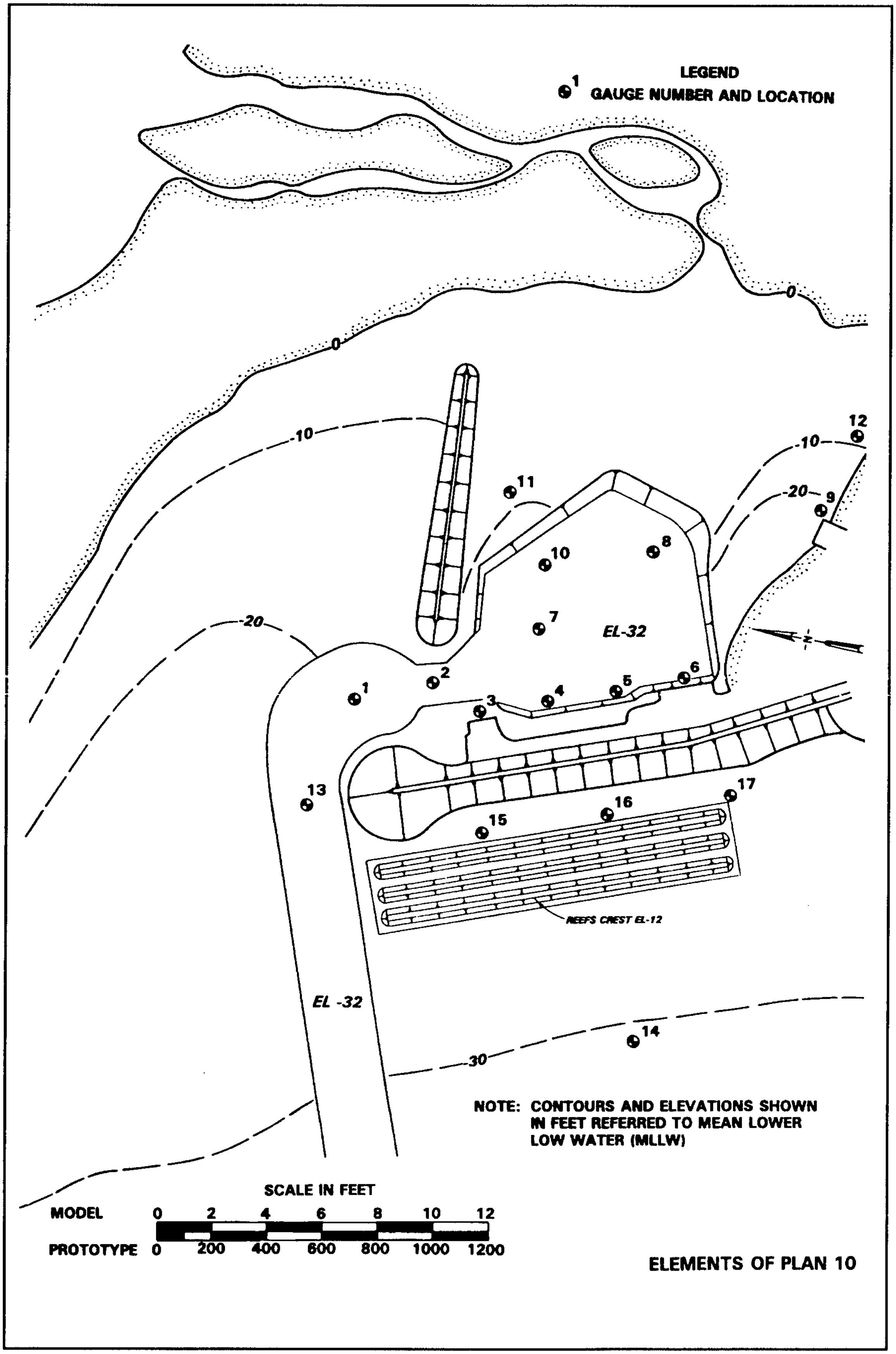
ELEMENTS OF PLAN 5



ELEMENTS OF PLANS 6-7



ELEMENTS OF PLANS 8-9



LEGEND
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0
-10
-20
-30
EL-32
EL -32
REEFS CREST EL-12
1
2
3
4
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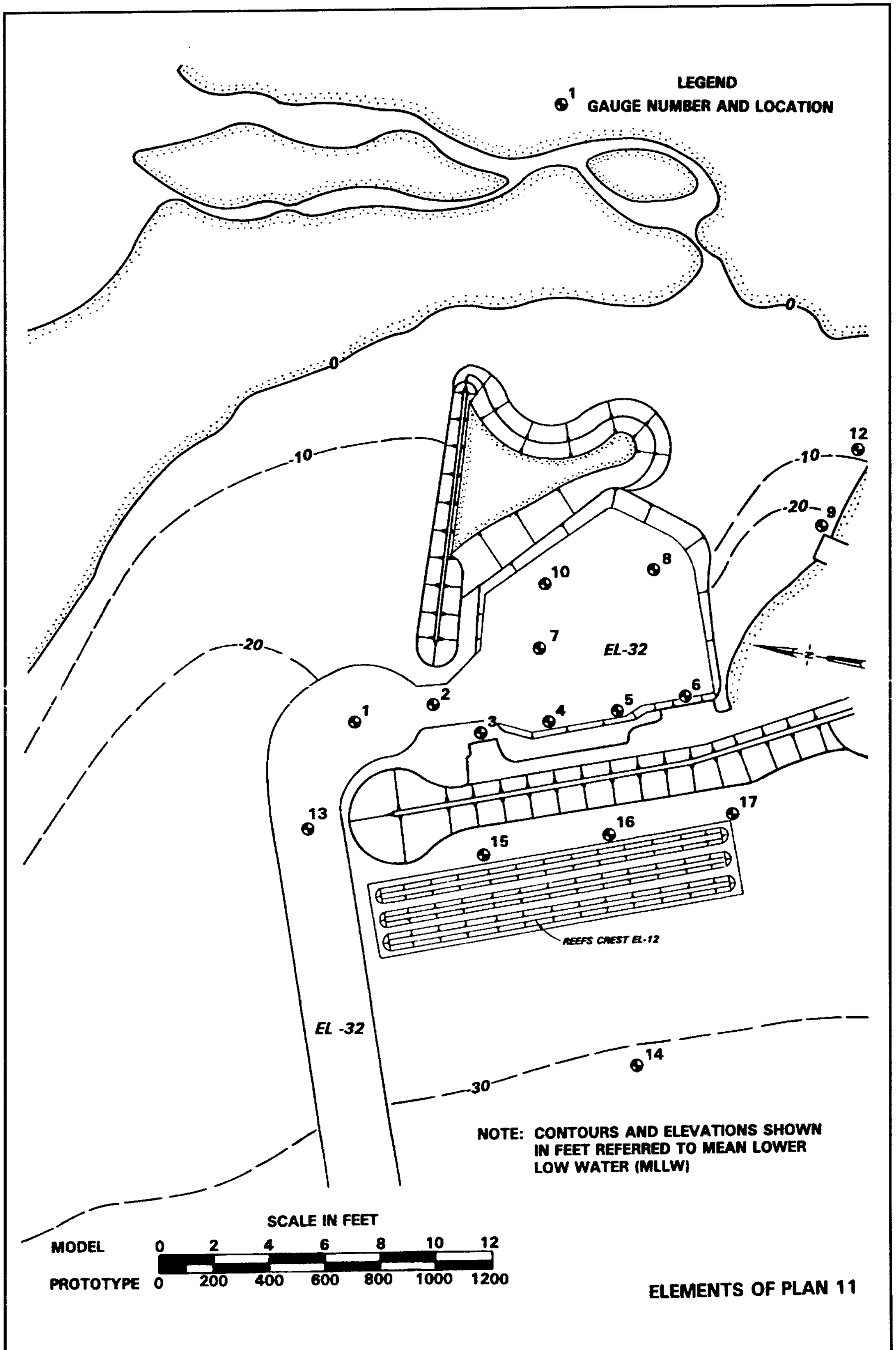
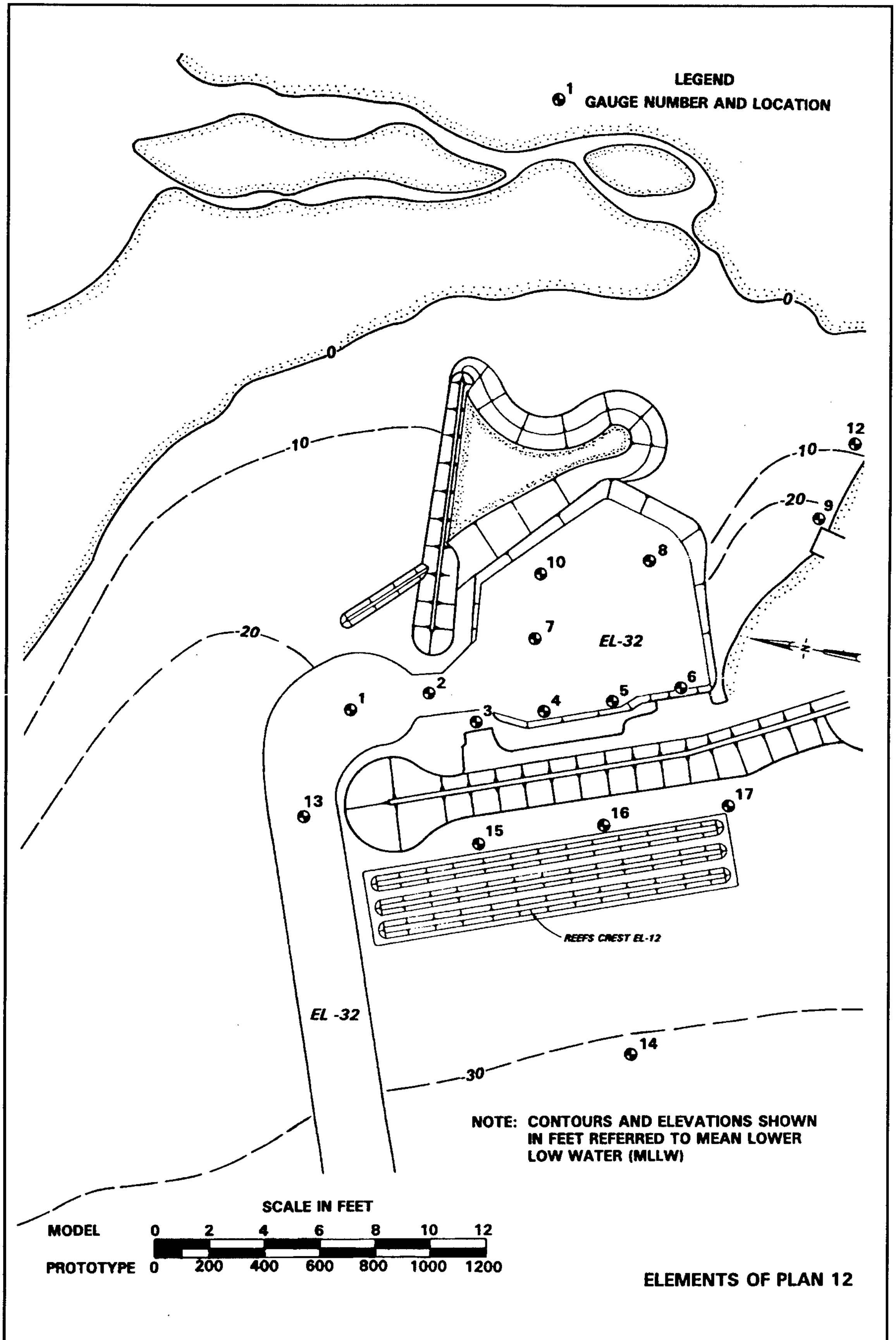
6
7
8
9
10
11
12
13
14
15
16
17
NOTE: CONTOURS AND ELEVATIONS SHOWN IN FEET REFERRED TO MEAN LOWER LOW WATER (MLLW)
SCALE IN FEET
MODEL 0 2 4 6 8 10 12
PROTOTYPE 0 200 400 600 800 1000 1200
ELEMENTS OF PLAN 10



ELEMENTS OF PLAN 11



ELEMENTS OF PLAN 12

REPORT DOCUMENTATION PAGE

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Robert R. Bottin, Jr.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A 1:100-scale (undistorted) three-dimensional coastal hydraulic model was used to investigate the design of proposed harbor improvements at St. Paul Harbor, St. Paul Island, Alaska, with respect to wave and current conditions in the harbor and sediment patterns at the site. Wave-induced circulation and sediment patterns seaward of the main breakwater as a result of a submerged reef also were investigated. The model reproduced approximately 2,865 m (9,400 ft) of the St. Paul Island shoreline, the existing harbor, the surface area of Salt Lagoon with its connecting channels to the harbor, and sufficient offshore area in the Bering Sea to permit generation of the required test waves. Proposed improvements consisted of deepening the entrance channel, constructing a maneuvering area and installing a wave dissipating spending beach inside the existing harbor, and constructing a submerged reef seaward of the main breakwater. An 18.3-m-long (60-ft-long) unidirectional, spectral wave generator, an automated data acquisition and control system, and a crushed coal tracer material were used in model operation. It was concluded from test results that:

a. During periods of severe storm wave activity with extreme high-tide conditions, wave heights in the existing harbor will exceed 1.7 m (5.5 ft) along the dock in the lee of the main breakwater and 0.8 m (2.5 ft) at the TDX Dock.

(Continued)

14. SUBJECT TERMS

Harbors	St. Paul Harbor, St. Paul Island, Alaska
Hydraulic models	Wave dissipating landfill
Reef breakwaters	Wave-induced currents
Sediment patterns	Wave protection

15. NUMBER OF PAGES
106

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

13. (Concluded).

b. For existing conditions, currents enter the harbor through the opening at the shoreward end of the detached breakwater and move in a clockwise direction exiting through the entrance. Maximum velocities along the shoreline inside the harbor will exceed 2.5 mps (8 fps). Currents also move seaward along the seaside of the detached breakwater across the harbor entrance.

c. For existing conditions, sediment moves southerly along the boulder spit and enters the harbor through the opening at the shoreward end of the detached breakwater. Sediment also moves westerly along the seaside of the detached breakwater toward the harbor entrance.

d. Test results obtained for the initial submerged reefs (Plans 1 and 2) indicated the structures would have no adverse impact on current patterns and magnitudes or sediment tracer patterns and deposits seaward of the main breakwater.

e. An extension of the initial submerged reefs northerly by 122 m (400 ft) in length (Plan 4) will decrease wave heights in the approach and entrance channels and result in improved navigation conditions.

f. A 15.2-m (50-ft) reduction in the length of the submerged reefs (from 396 to 381 m (1,300 to 1,250 ft)) on their southern end (Plan 9) will not increase wave conditions in the harbor.

g. Test results for the deepened channel and maneuvering area and the 381-m-long (1,250-ft-long) submerged reefs of Plan 10 indicated that wave heights would increase at the TDX Dock and the inner harbor area when compared to existing conditions.

h. Installation of the wave-dissipating spending beach in the harbor (Plan 11) with the deepened channel and maneuvering area and the 381-m-long (1,250-ft-long) submerged reefs will result in reduced wave conditions. Wave heights throughout the harbor will be significantly less than those obtained for existing conditions.

i. Installation of Plan 10 (deepened channel and maneuvering area and the 381-m-long (1,250-ft-long) submerged reefs) or Plan 11 (addition of the wave-dissipating spending beach) will have no adverse impact on current patterns and magnitudes and/or sediment patterns and subsequent deposits in the vicinity of the harbor.

j. The 120-m-long (400-ft-long) breakwater spur of Plan 12 will have no adverse impact on wave or current conditions in the harbor. It will, however, redirect sediment movement and subsequent deposits from the entrance channel to the northerly edge of the channel, and thus, reduce the potential for shoaling.

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